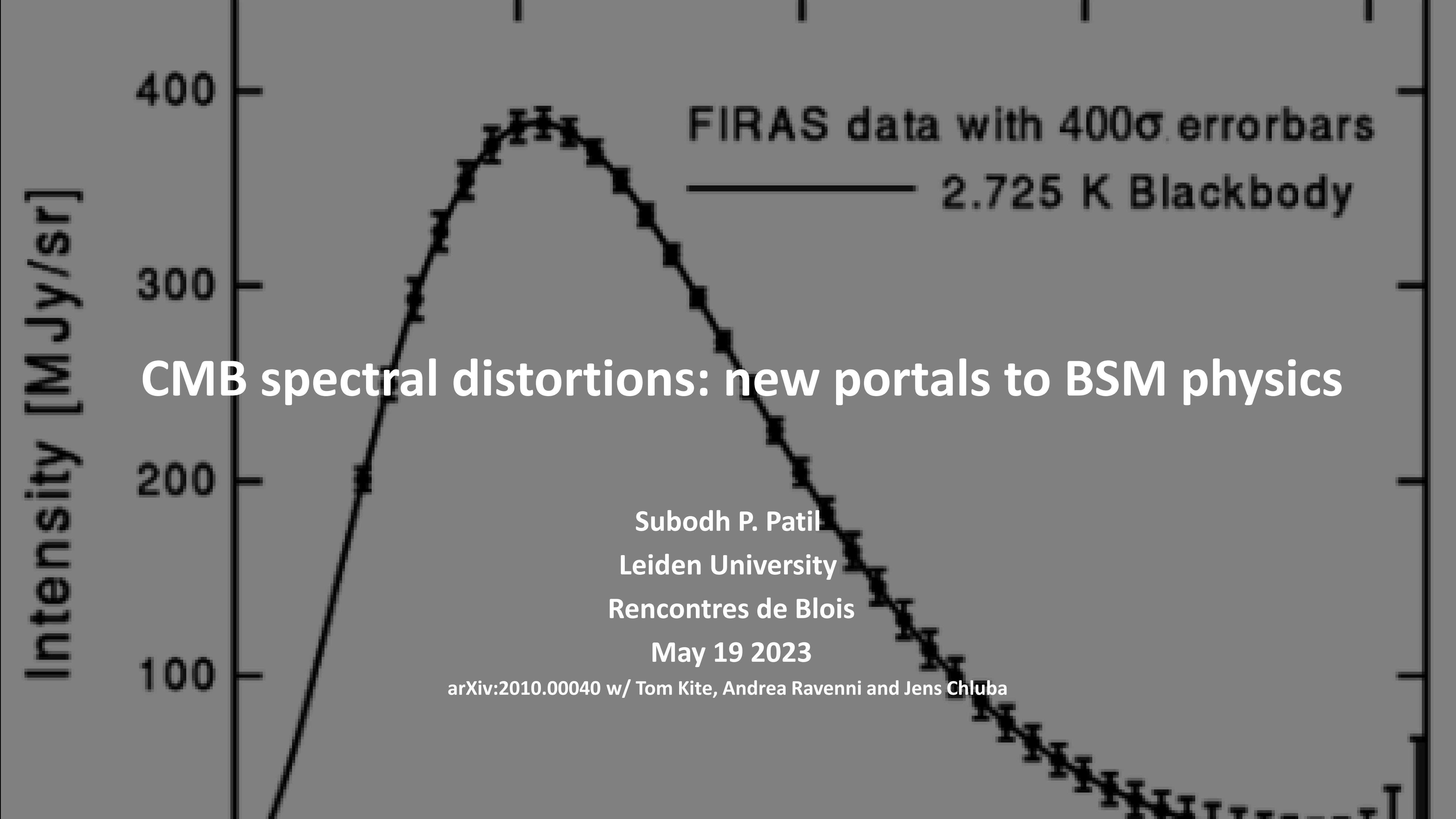
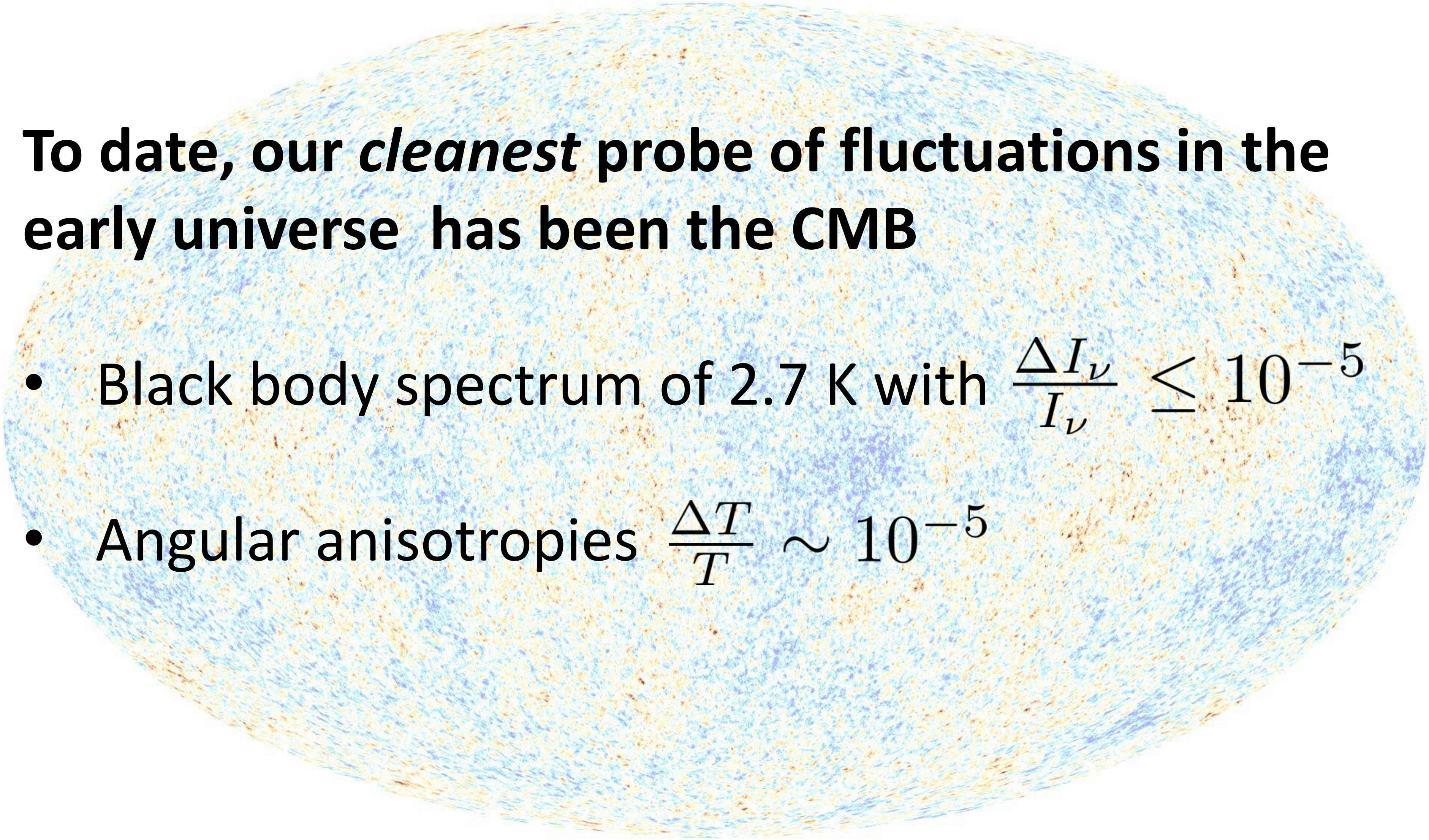


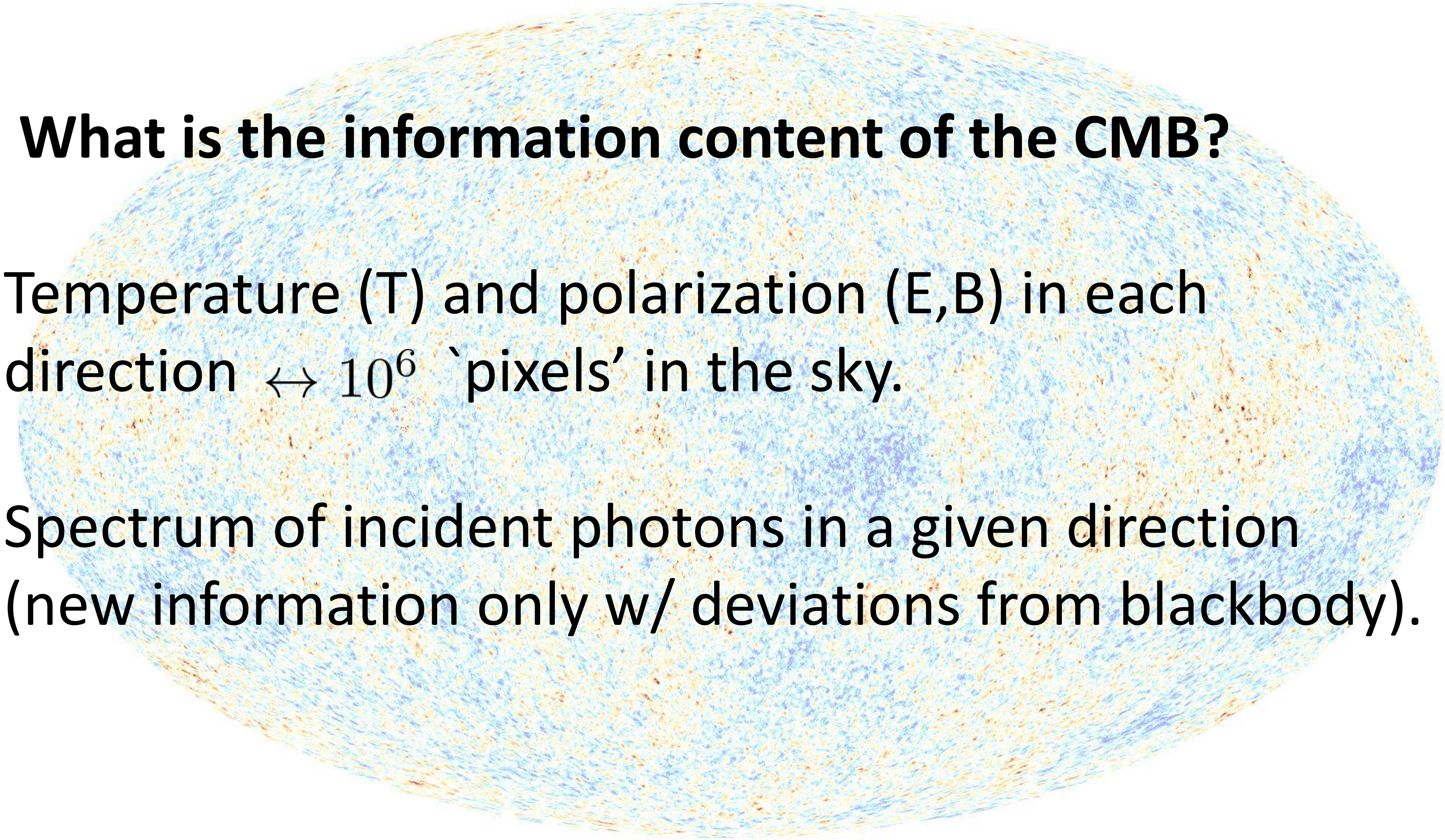
CMB spectral distortions: new portals to BSM physics

Subodh P. Patil
Leiden University
Rencontres de Blois
May 19 2023
arXiv:2010.00040 w/ Tom Kite, Andrea Ravenni and Jens Chluba



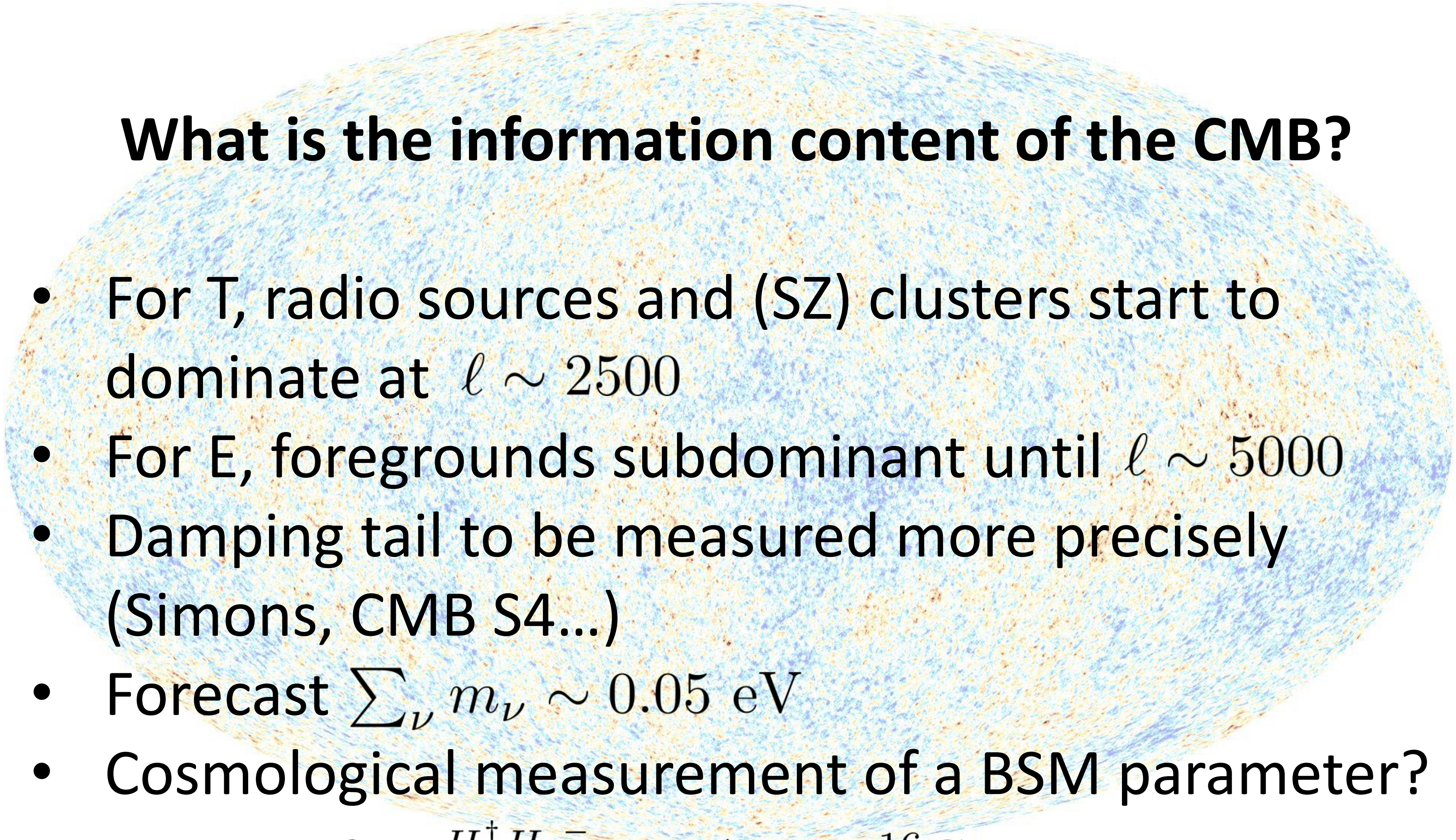
To date, our *cleanest* probe of fluctuations in the early universe has been the CMB

- Black body spectrum of 2.7 K with $\frac{\Delta I_\nu}{I_\nu} \leq 10^{-5}$
- Angular anisotropies $\frac{\Delta T}{T} \sim 10^{-5}$



What is the information content of the CMB?

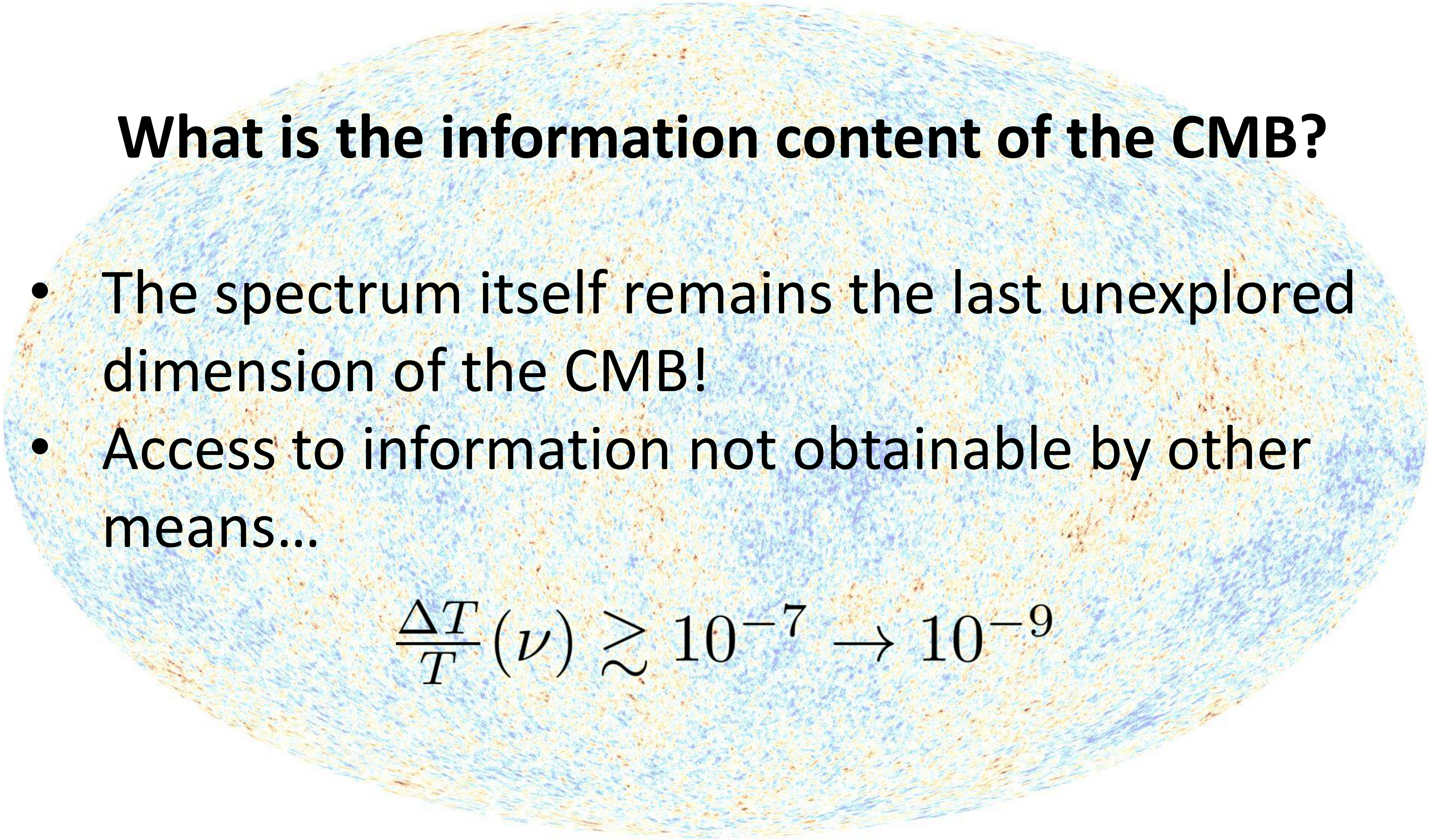
- Temperature (T) and polarization (E,B) in each direction $\leftrightarrow 10^6$ `pixels’ in the sky.
- Spectrum of incident photons in a given direction (new information only w/ deviations from blackbody).



What is the information content of the CMB?

- For T, radio sources and (SZ) clusters start to dominate at $\ell \sim 2500$
- For E, foregrounds subdominant until $\ell \sim 5000$
- Damping tail to be measured more precisely (Simons, CMB S4…)
- Forecast $\sum_\nu m_\nu \sim 0.05 \text{ eV}$
- Cosmological measurement of a BSM parameter?

$$\mathcal{L} \supset \frac{H^\dagger H}{\Lambda} \bar{\psi}\psi; \quad \Lambda \sim 10^{16}\text{GeV}$$

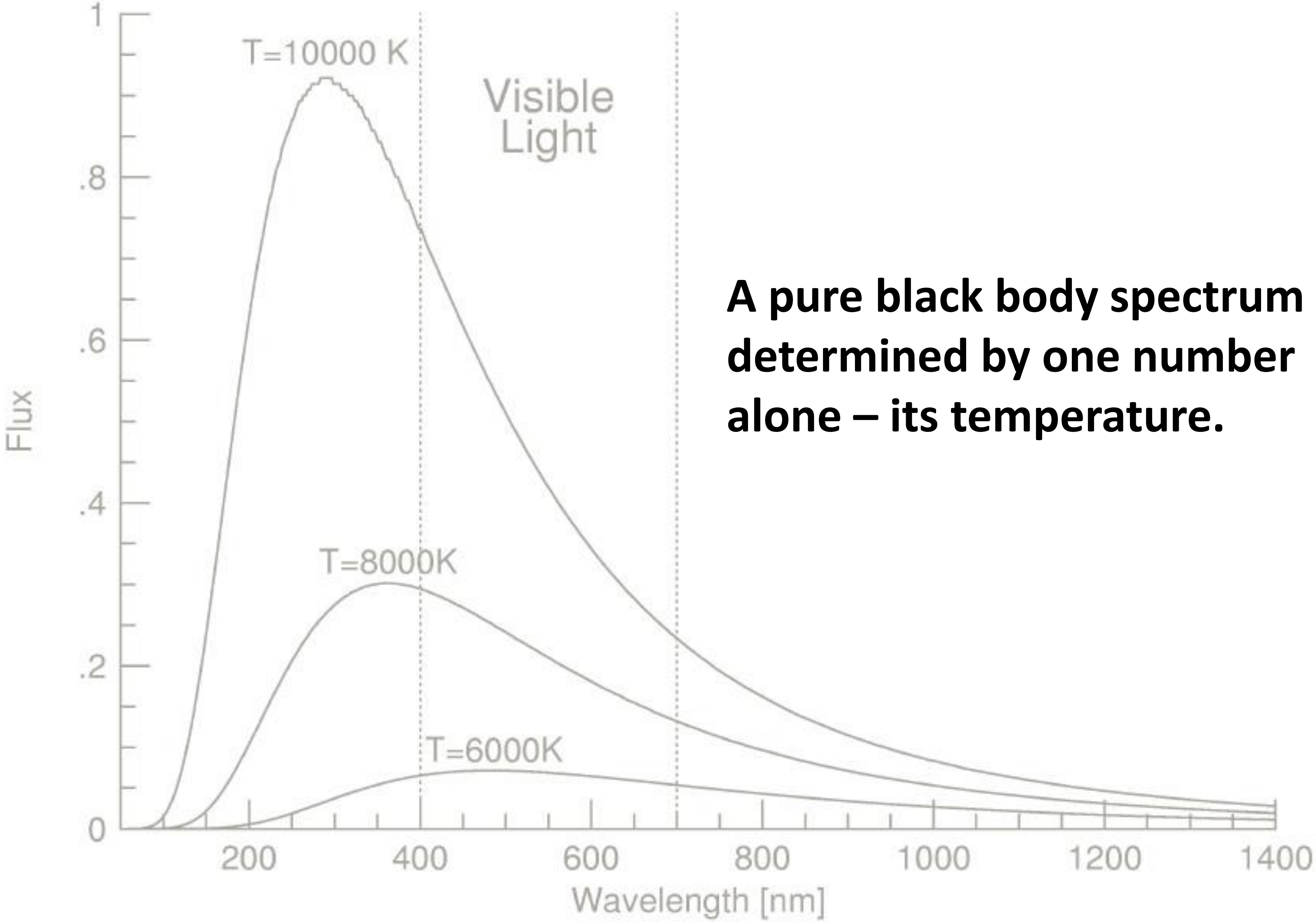


What is the information content of the CMB?

- The spectrum itself remains the last unexplored dimension of the CMB!
- Access to information not obtainable by other means…

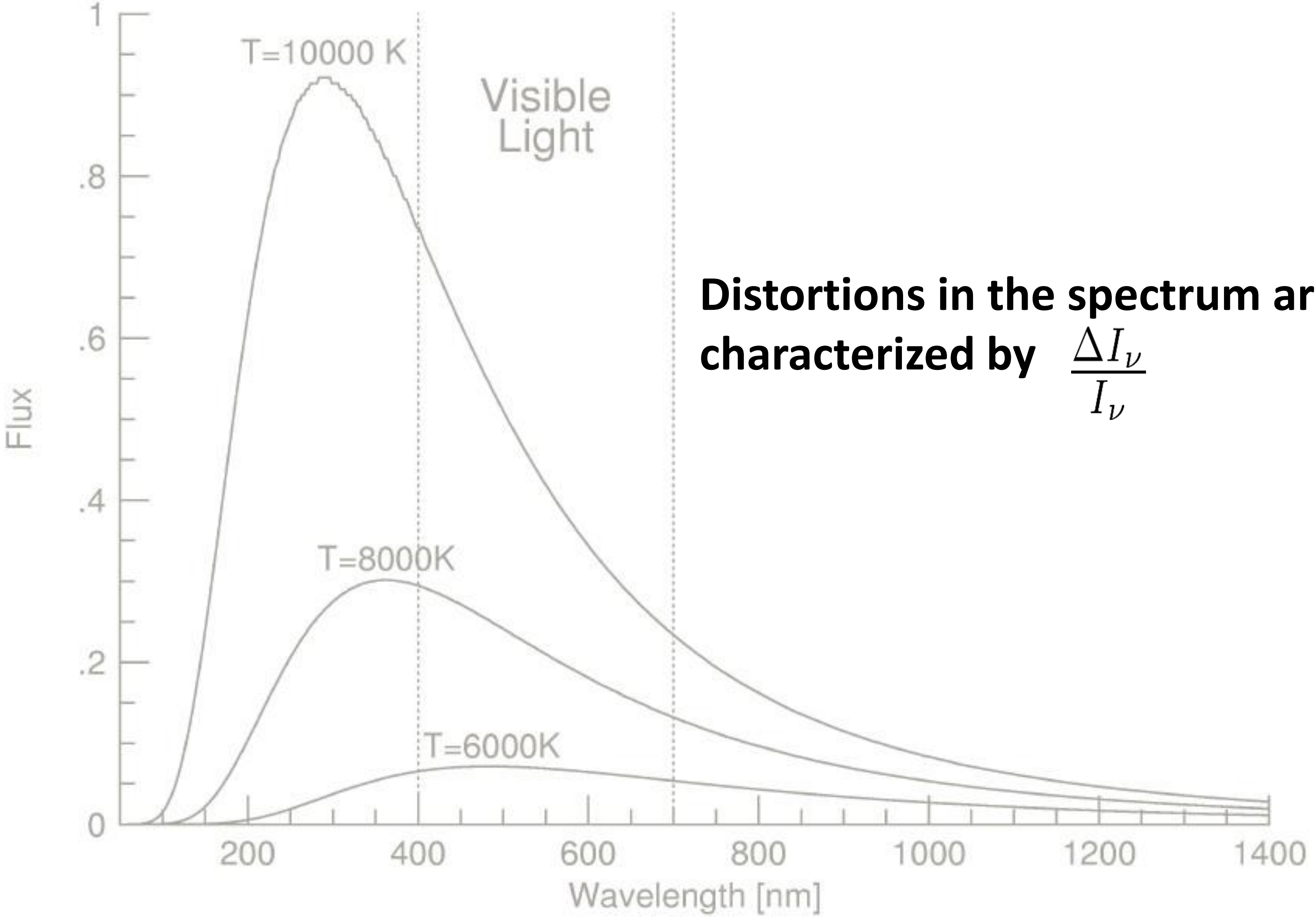
$$\frac{\Delta T}{T}(\nu) \gtrsim 10^{-7} \to 10^{-9}$$

CMB spectral distortions



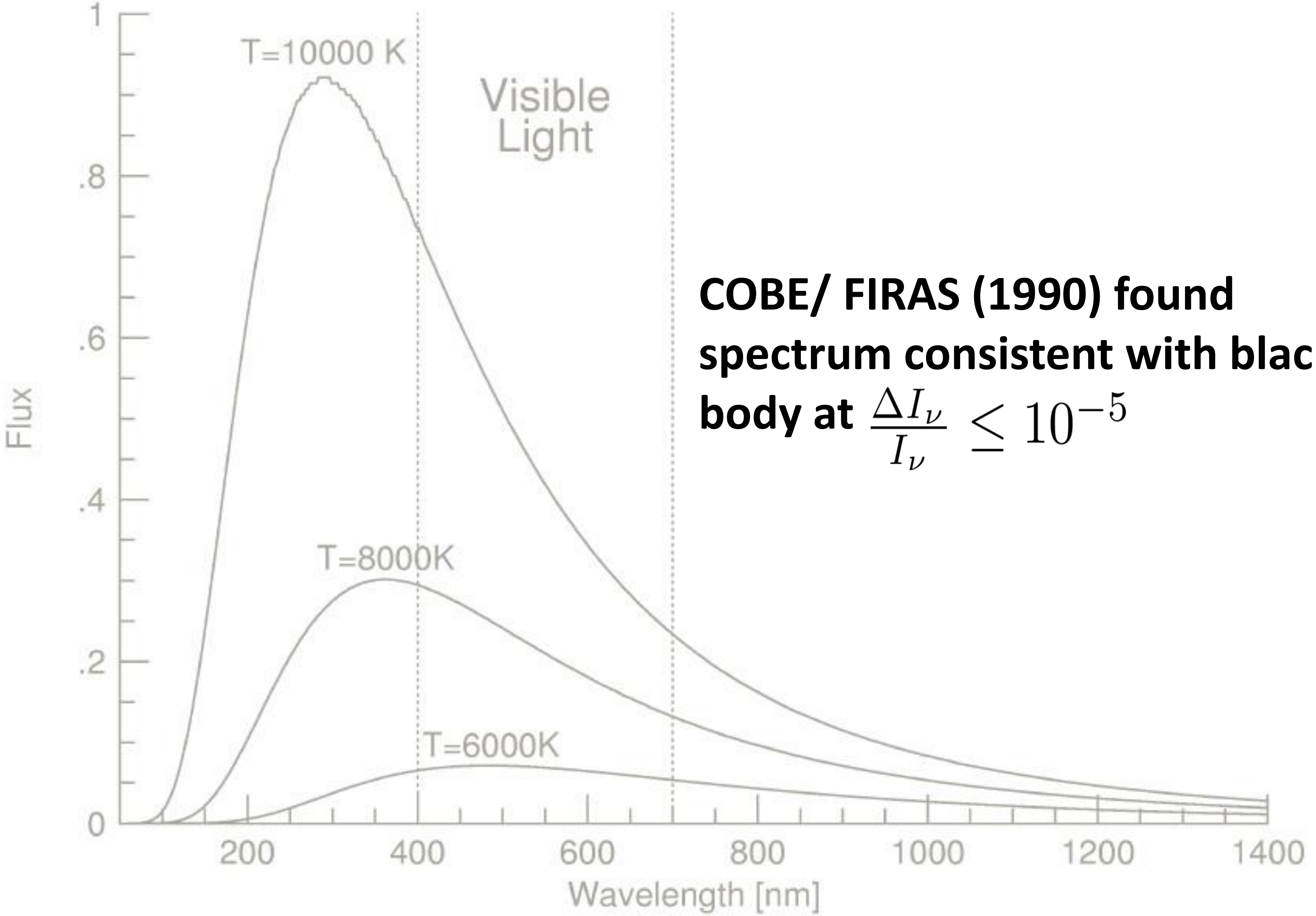
A pure black body spectrum is determined by one number alone – its temperature.

CMB spectral distortions



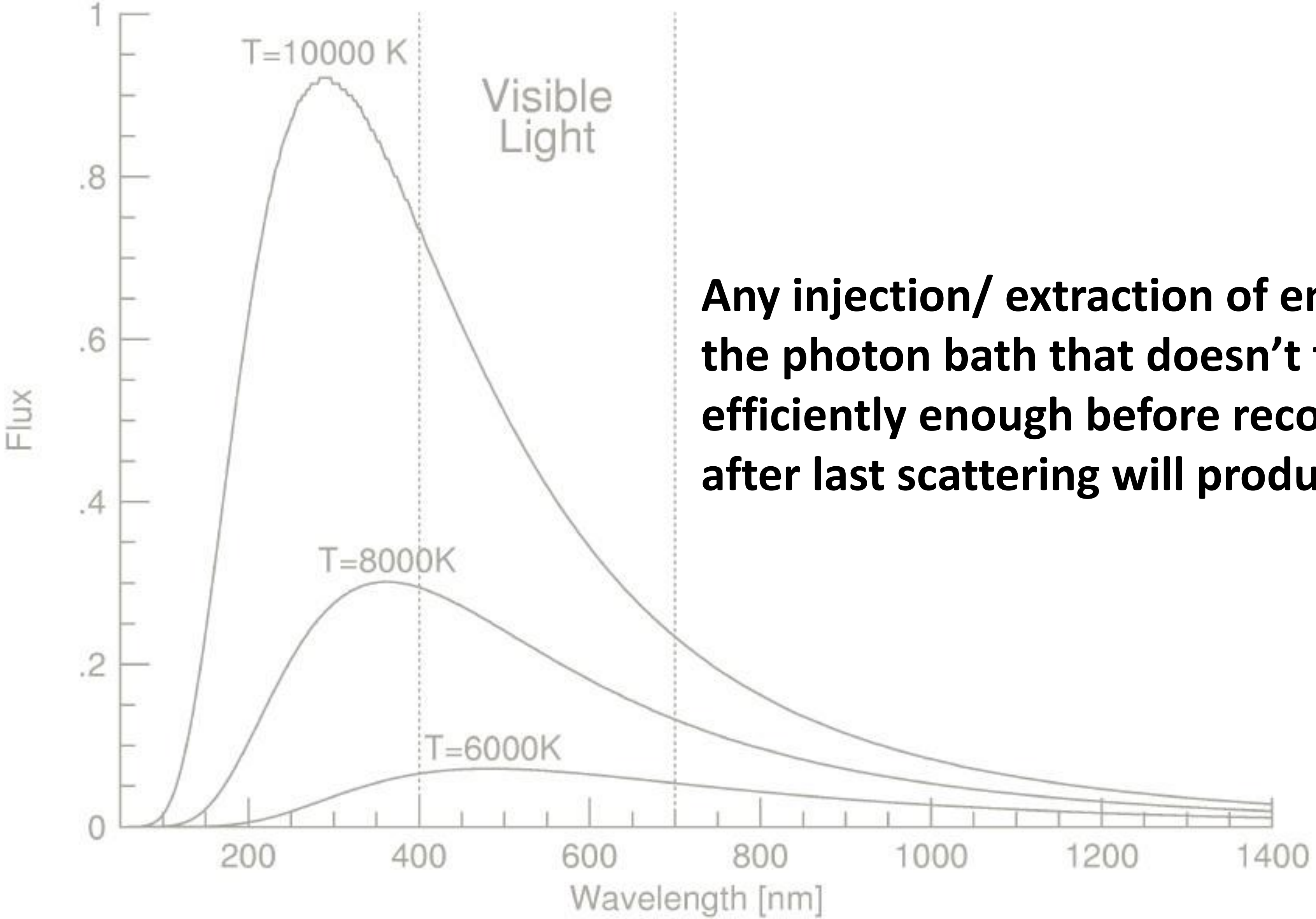
Distortions in the spectrum are characterized by $\frac{\Delta I_\nu}{I_\nu}$

CMB spectral distortions



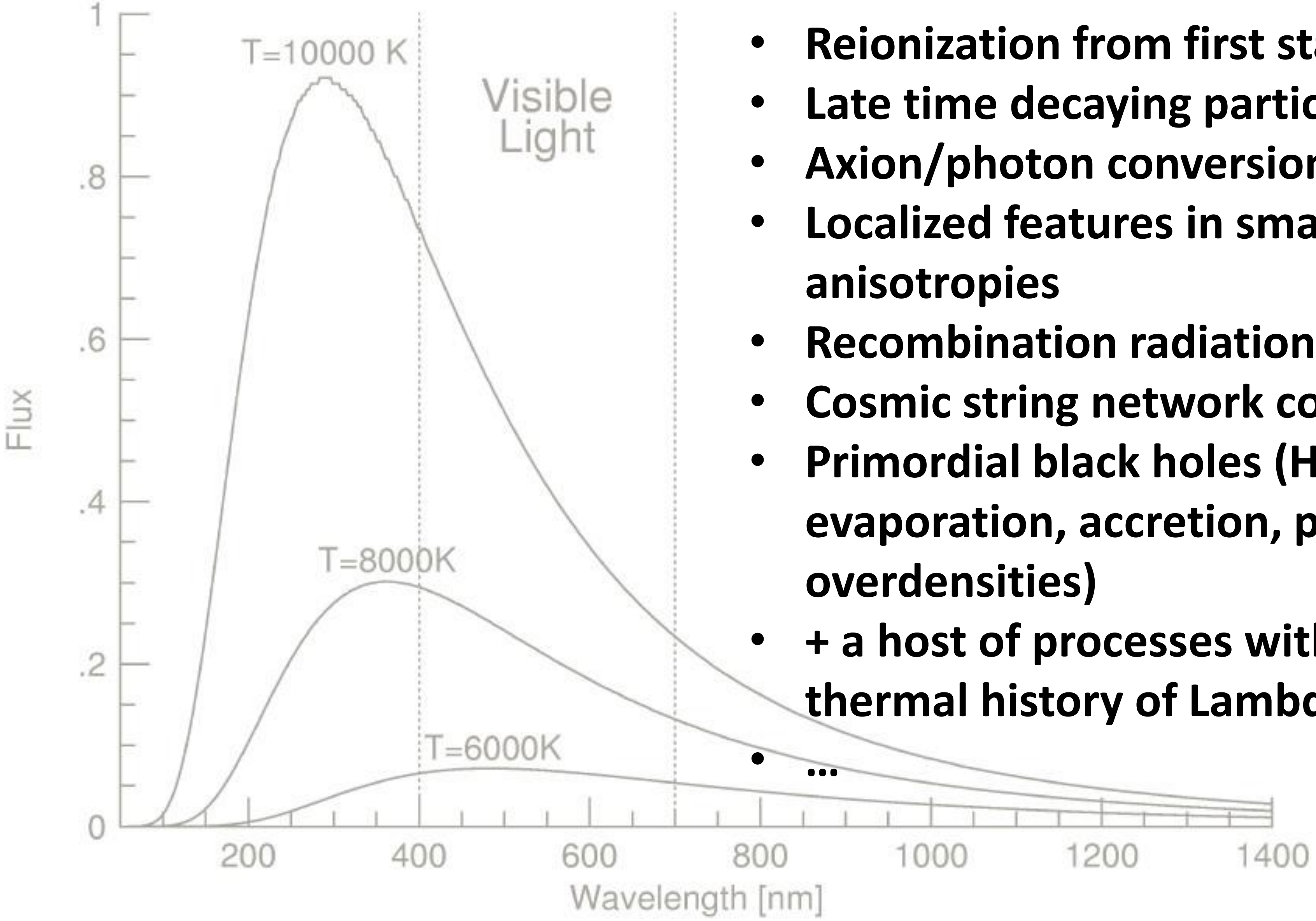
COBE/ FIRAS (1990) found spectrum consistent with black body at $\frac{\Delta I_\nu}{I_\nu} \leq 10^{-5}$

CMB spectral distortions



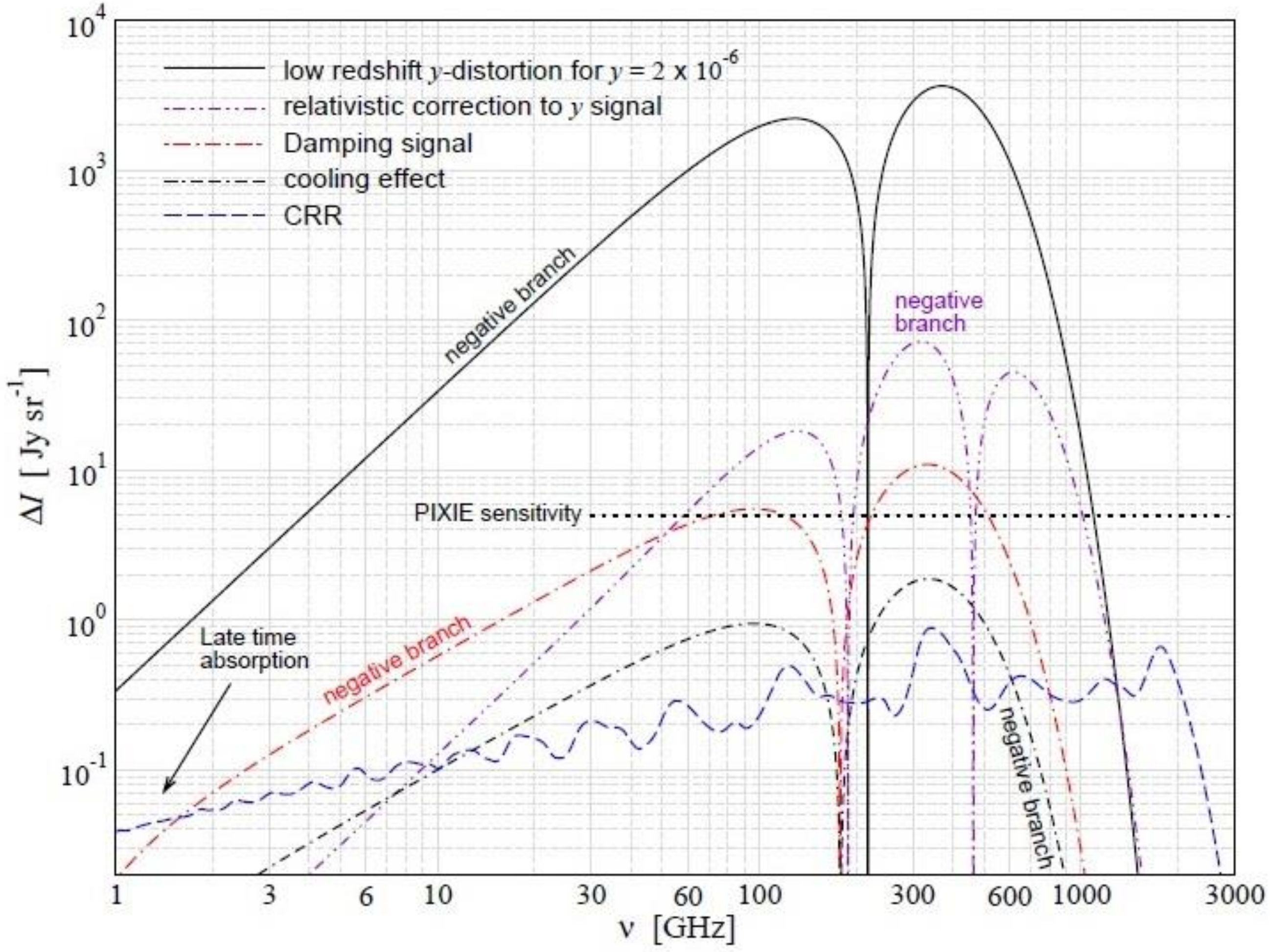
Any injection/ extraction of energy into/ from the photon bath that doesn't thermalize efficiently enough before recombination, or after last scattering will produce distortions…

CMB spectral distortions



- **Reionization from first stars**
- **Late time decaying particles**
- **Axion/photon conversion**
- **Localized features in small scale anisotropies**
- **Recombination radiation of H, He**
- **Cosmic string network collapse**
- **Primordial black holes (Hawking evaporation, accretion, primordial overdensities)**
- **+ a host of processes within the standard thermal history of Lambda CDM**
- **…**

CMB spectral distortions

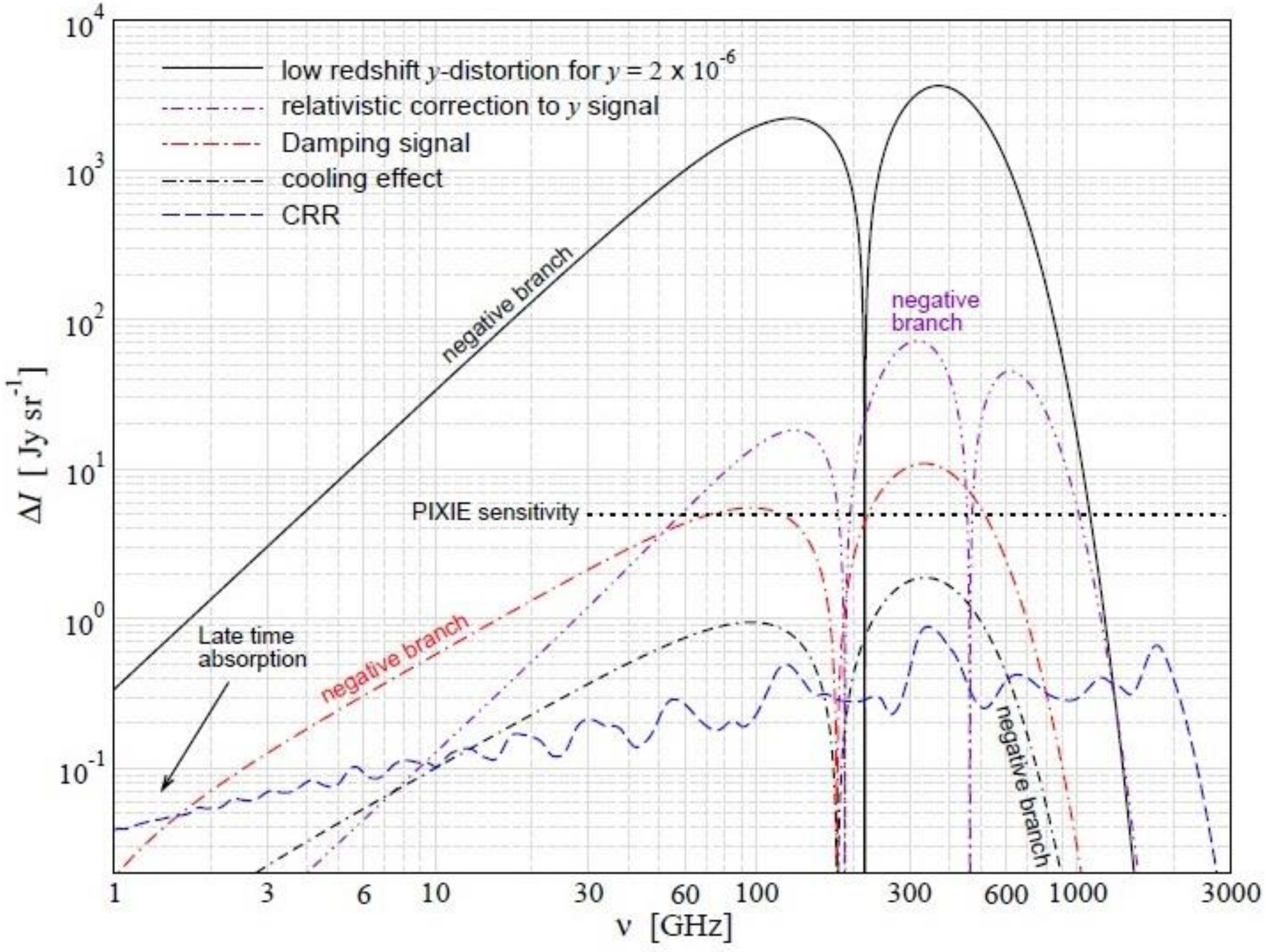


Reionization `bump' at $\frac{\Delta I_\nu}{I_\nu} \sim 10^{-6} - 10^{-7}$

Decaying particles/ small scale features at $\frac{\Delta I_\nu}{I_\nu} \sim 10^{-8} - 10^{-9}$

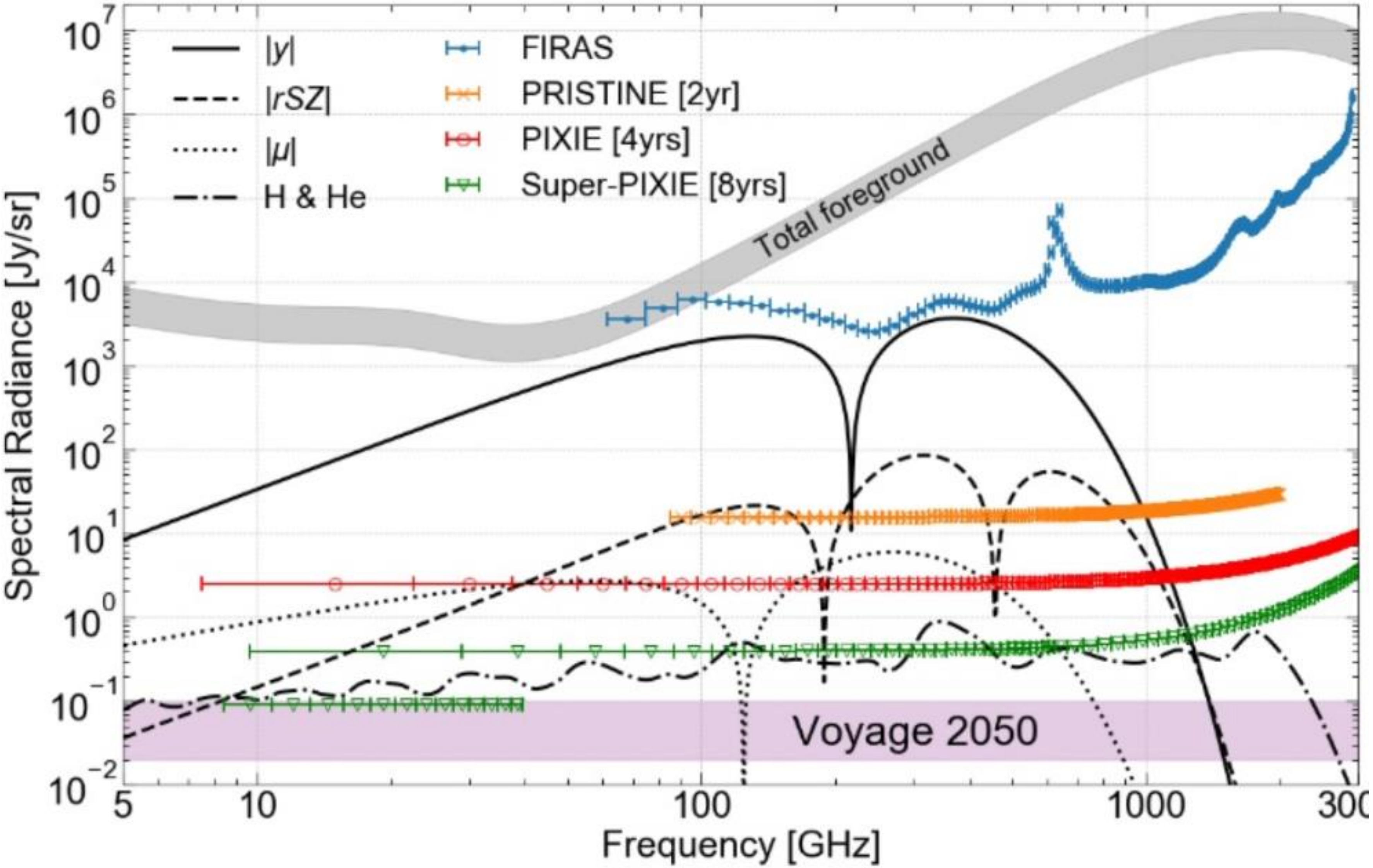
(Fig. courtesy J. Chluba)

CMB spectral distortions



Recombination lines plausibly observable from the ground (cf. APSERA PI: **Mayuri Rao @RRI Bangalore**)

(Fig. courtesy J. Chluba)



|y|
|rSZ|
|μ|
H & He
FIRAS
PRISTINE [2yr]
PIXIE [4yrs]
Super-PIXIE [8yrs]
Total foreground
Voyage 2050
Spectral Radiance [Jy/sr]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
5
10
100
1000
300
Frequency [GHz]

CMB spectral distortions and BSM physics I

[Or, a laundry list of projects for anyone with a string/ BSM phenomenological predisposition… if this is you **feel free to get in touch!**]

Any particles that decay within the window $10^7 < z < 10^3$ with any branching ration to charged particles or photons can result in SD.

i.e. for lifetimes $10^6 < \tau < 10^{14} s$

For gravitationally suppressed decays $\tau \sim \frac{M_{\rm pl}^2}{m^3}$

Gravitinos (already studied), moduli fields, dilatons, KK resonances 100 GeV – 100 MeV

Constraining power on string/ beyond Standard Model phenomenological scenarios

CMB spectral distortions and BSM physics I

[Or, a laundry list of projects for anyone with a string/ BSM phenomenological predisposition… if this is you **feel free to get in touch!**]

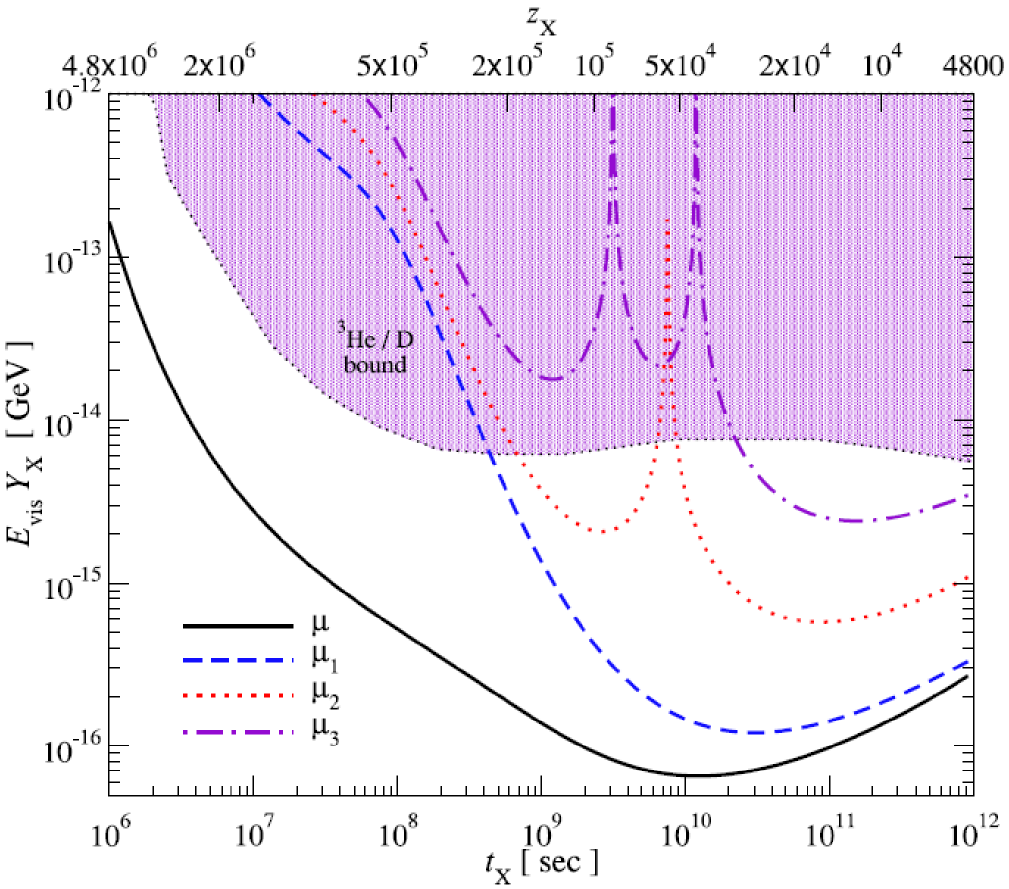


FIG. 1: $E_{\rm vis}$:= mass × branching ratio into photons; $Y_X := n_X/S$ is the relic density of species X relative to the entropy density [6].

(Fig. courtesy J. Chluba and D. Jeong)

Outline

- **An overview of basic physics of spectral distortions**
- **The different types of spectral distortions**
- **Dissipation of scalar modes;** $1 \lesssim k \lesssim 10^4 \ \mathrm{Mpc}^{-1}$
- **Dissipation of tensor modes;** $1 \lesssim k \lesssim 10^6 \ \mathrm{Mpc}^{-1}$
- **SDs as a stochastic GW background detector in the sky**
- **Constraints on various phenomenological scenarios**
- **Experimental concepts/ proposals on the table**

Spectral distortions primer

A black body spectrum is entirely characterized by one number, *T*:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_\mathrm{B}T)} - 1}$$

Since $\rho_\gamma \propto T^4$ in thermal equilibrium, any injection of photons into the primordial plasma must be distributed according to $\simeq \frac{\partial B_\nu}{\partial T}$ in order to shift the temperature to $T \to T' = T + \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma}$

If this is not true, distortions in the spectrum will result…
There are two `main' types of distortion: μ - distortions;

$$\widetilde{B}_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{(h\nu - \mu)/(k_\mathrm{B}T)} - 1}$$

… important at *z* > 50,000, when Compton scattering is efficient

Spectral distortions primer

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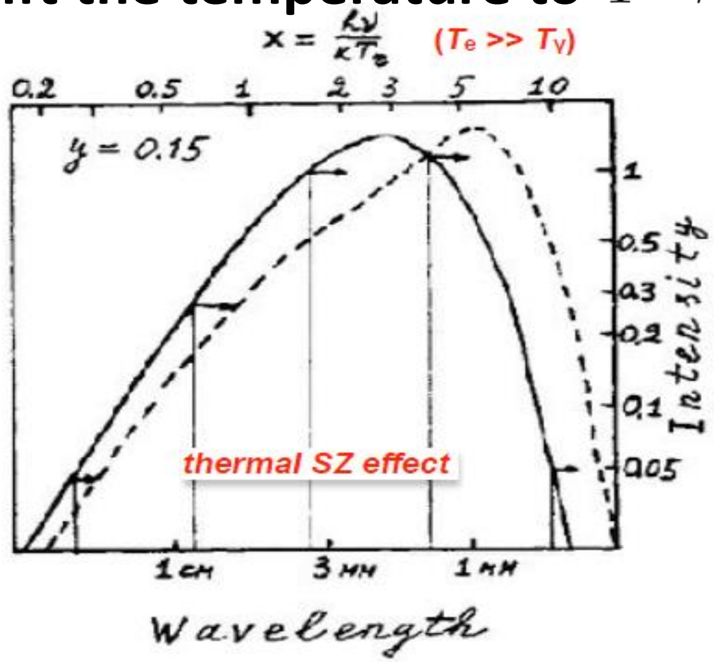

… and y-distortions; important at *z* < 50,000 (scattering is inefficient)

Fig. courtesy Sunyaev and Zeldovich

Spectral distortions primer

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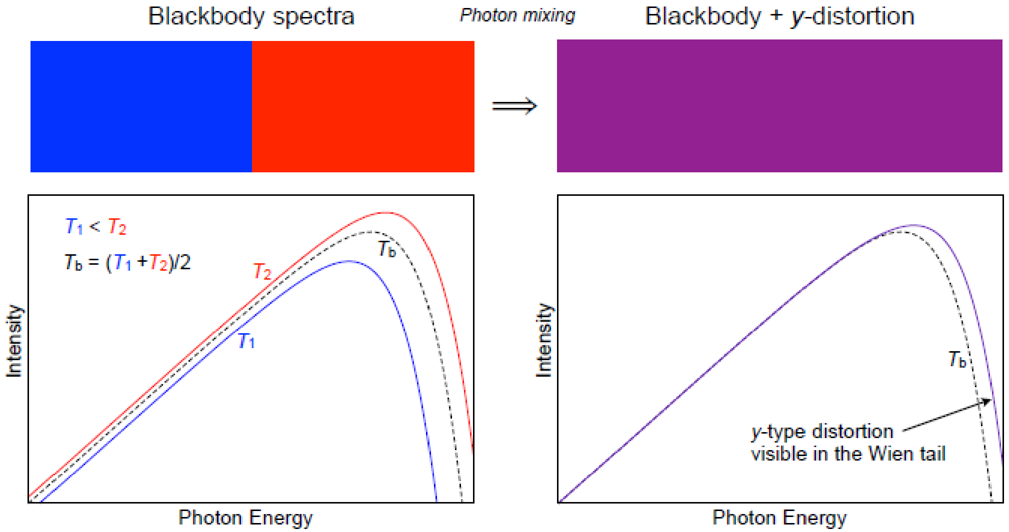
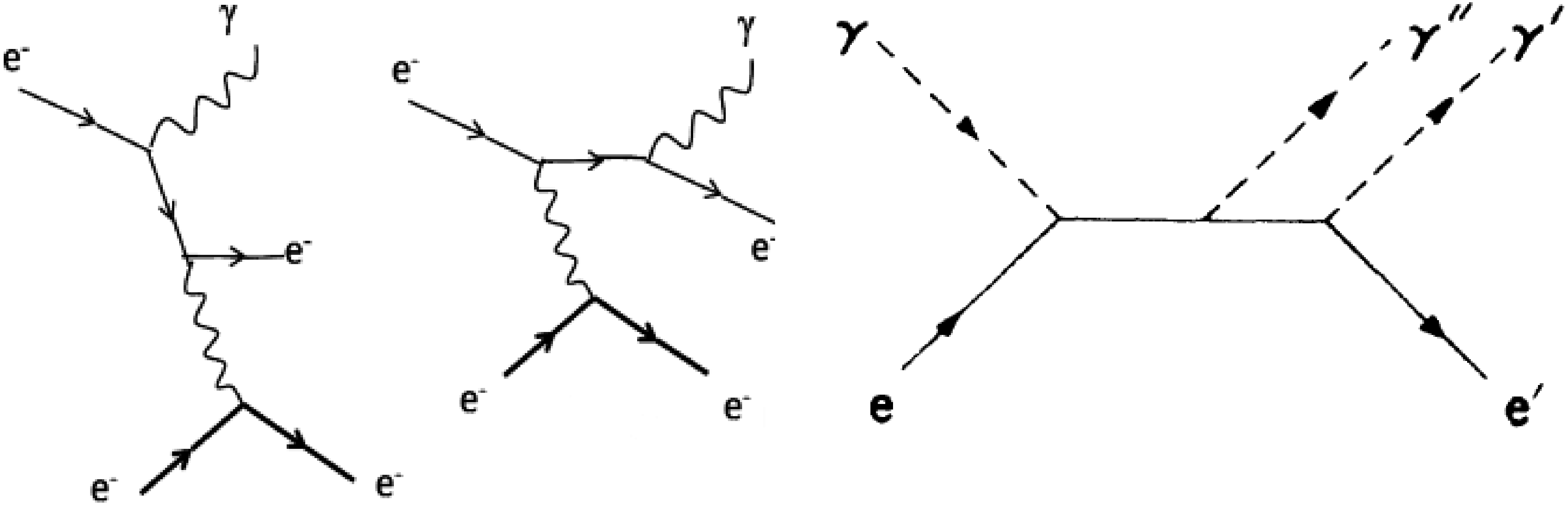


… and y-distortions; important at *z* < 50,000 (scattering is inefficient)

Chluba, Hamann, Patil (2015)

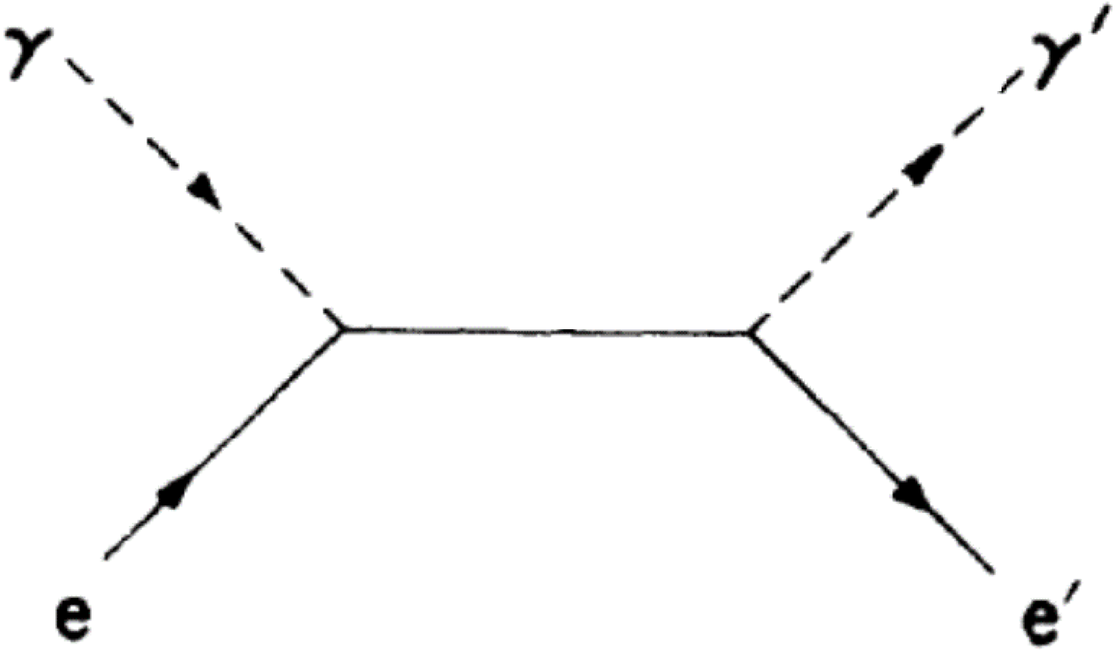
Spectral distortions primer

In the early universe, brehmsstrahlung and double Compton scattering affect the number of photons:



Spectral distortions primer

… whereas regular Compton scattering redistributes photons in phase space



For *z* > 10^6, Compton scattering is very efficient, thermalization is rapid.

Spectral distortions primer

Given an energy release history, can compute the distortion of the spectrum via a `thermal' Green's function formalism

$$\Delta I_\nu \approx \int G_{\rm th}\left(\nu, z'\right) \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}{\rm d}z'$$

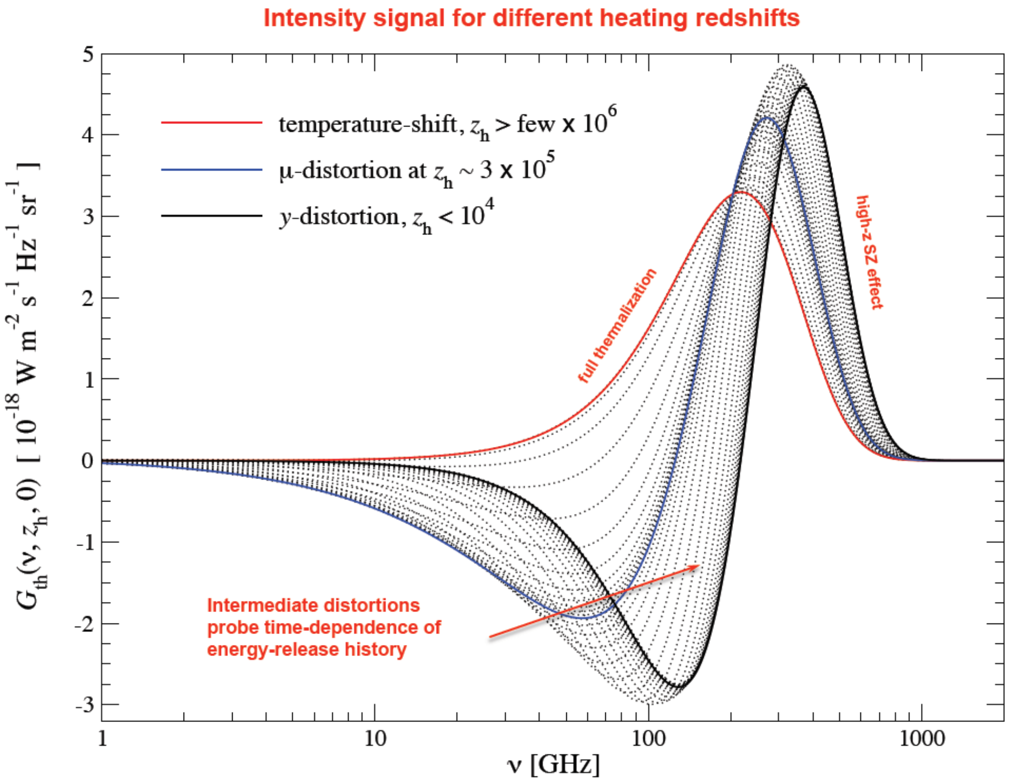
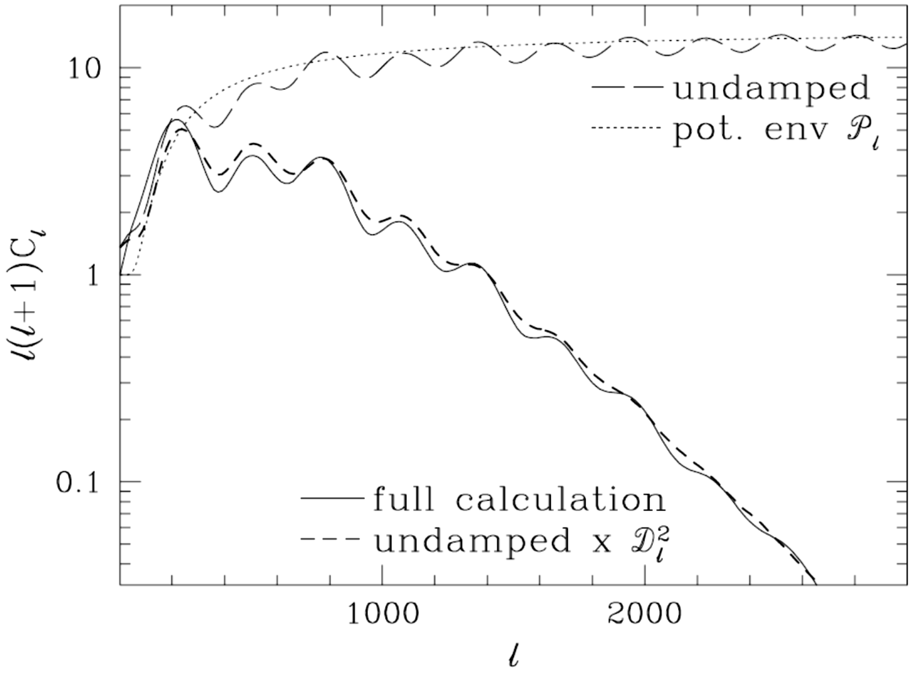


Fig. from Chluba, Hamann and Patil (2015)

Dissipation of scalar modes

Longitudinal perturbations in photon fluid dissipate due to free streaming and scattering (cf. the angular power spectrum if Silk damping didn't occur)



(Fig. courtesy W. Hu and M. White)

$$\mu_{\rm ac} \approx \int_{k_{\rm min}}^{\infty} \frac{k^2 {\rm d}k}{2\pi^2} P_{\mathcal{R}}(k) W_\mu(k)$$

$$y_{\rm ac} \approx \int_{k_{\rm min}}^{\infty} \frac{k^2 {\rm d}k}{2\pi^2} P_{\mathcal{R}}(k) W_y(k)$$

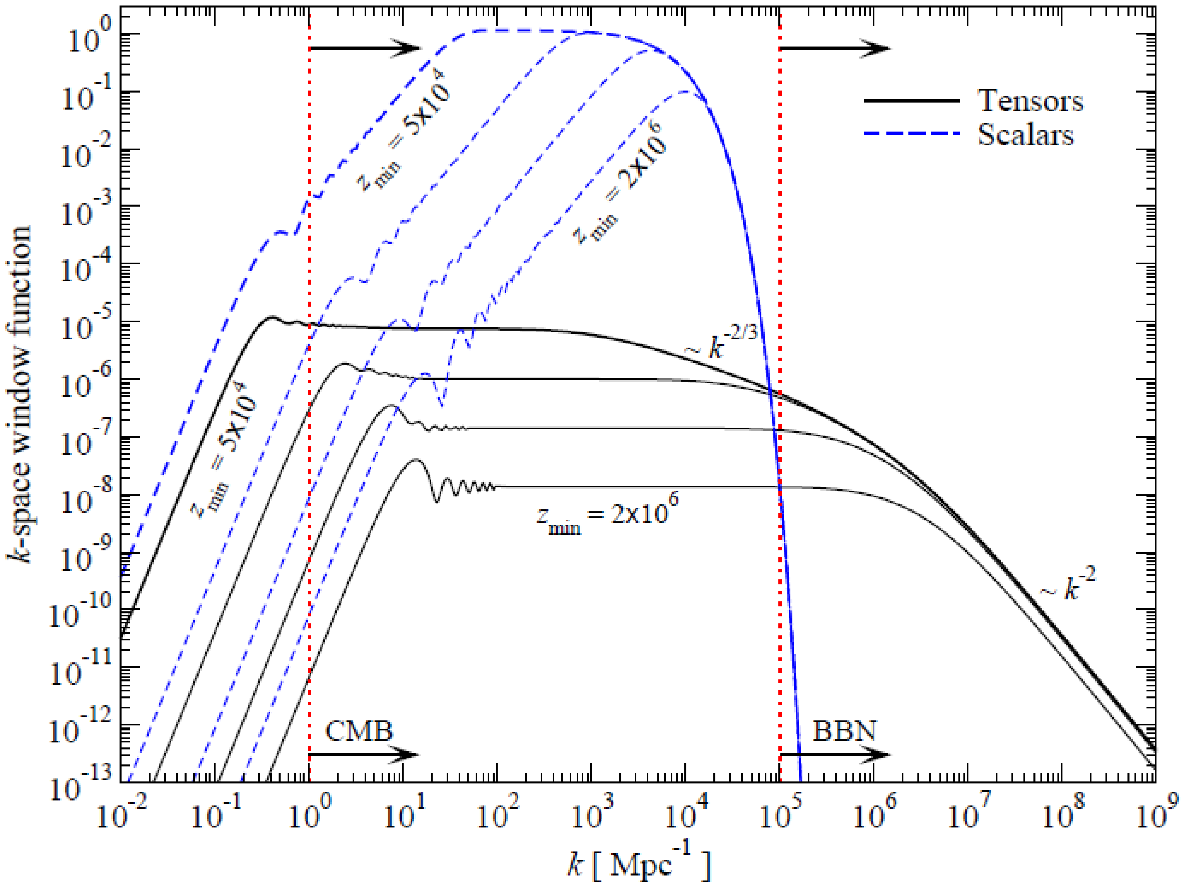
$$W_\mu(k) \approx 2.8A^2 \left[\exp\left(- \frac{\left[\frac{\hat{k}}{1360}\right]^2}{1+\left[\frac{\hat{k}}{260}\right]^{0.3}+\frac{\hat{k}}{340}} \right) - \exp\left(- \left[\frac{\hat{k}}{32}\right]^2 \right) \right]$$

$$W_y(k) \approx \frac{A^2}{2} \exp\left(- \left[\frac{\hat{k}}{32}\right]^2 \right) \qquad \hat{k} = k/\left[1{\rm Mpc}^{-1}\right]$$

Dissipation of tensor modes

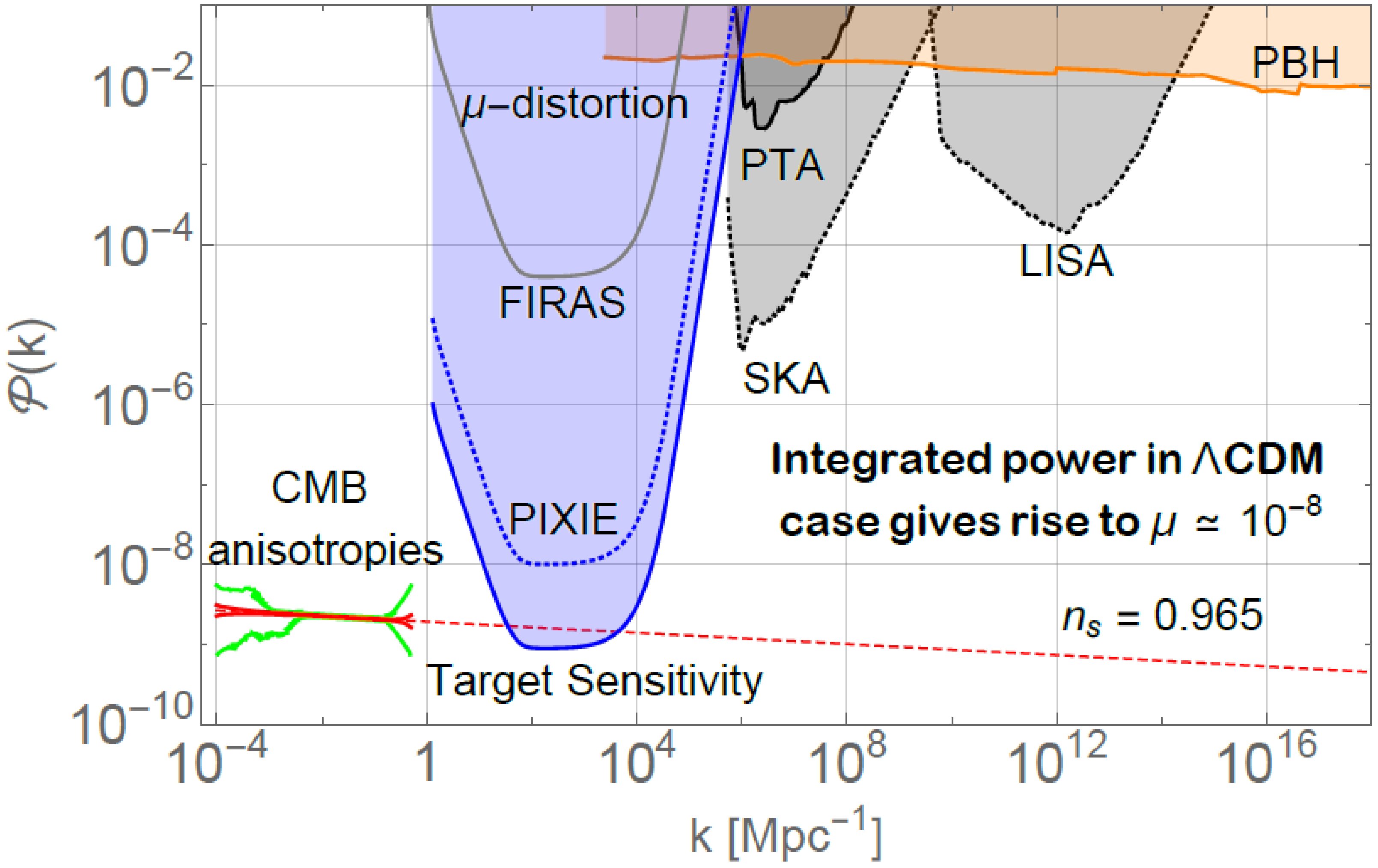
Whereas tensor perturbations dissipate mainly through just free streaming:

$$\mu_T \approx \int_0^\infty \frac{k^2 \mathrm{d}k}{2\pi^2} P_T(k) W_T(k)$$



Chluba, Dai, Grin, Amin and Kamionkowski (2014)

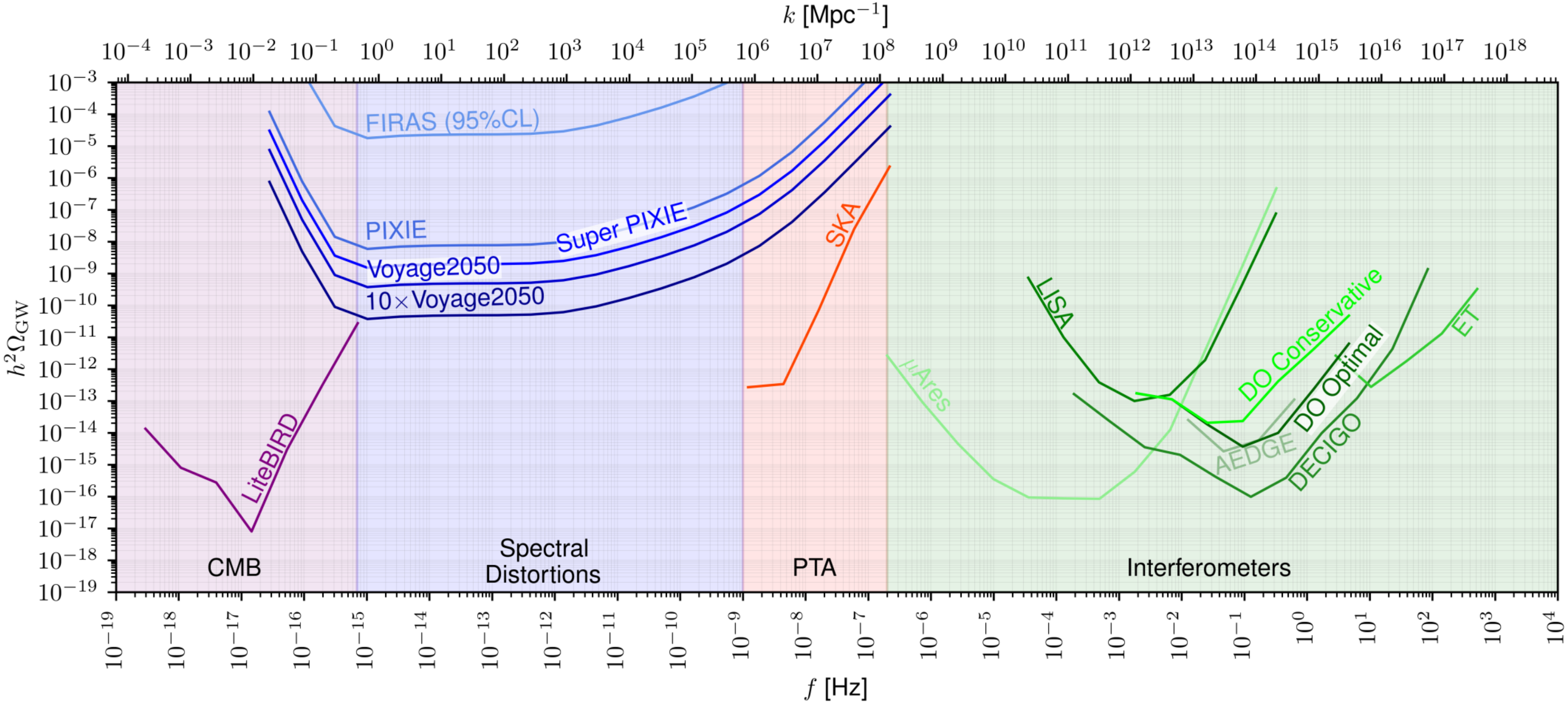
SDs probe small scale scalar power



Chluba, Kogut, Patil et al. (2019)

SDs probe tensor power

Spectral distortions can probe stochastic gravitational wave backgrounds at frequencies inaccessible to other probes (!)



(Fig. from Kite *et al*, 2010.00040)

SDs probe tensor power

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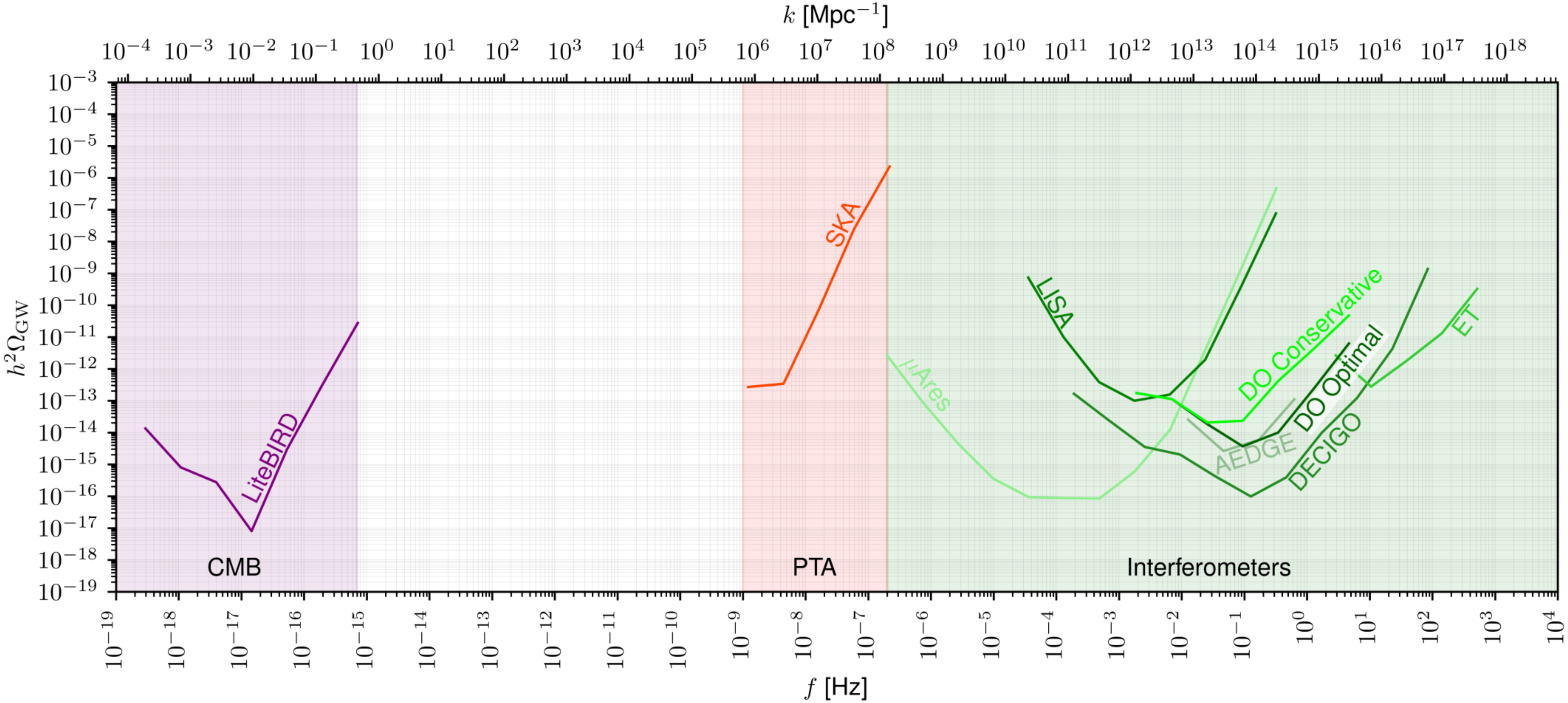
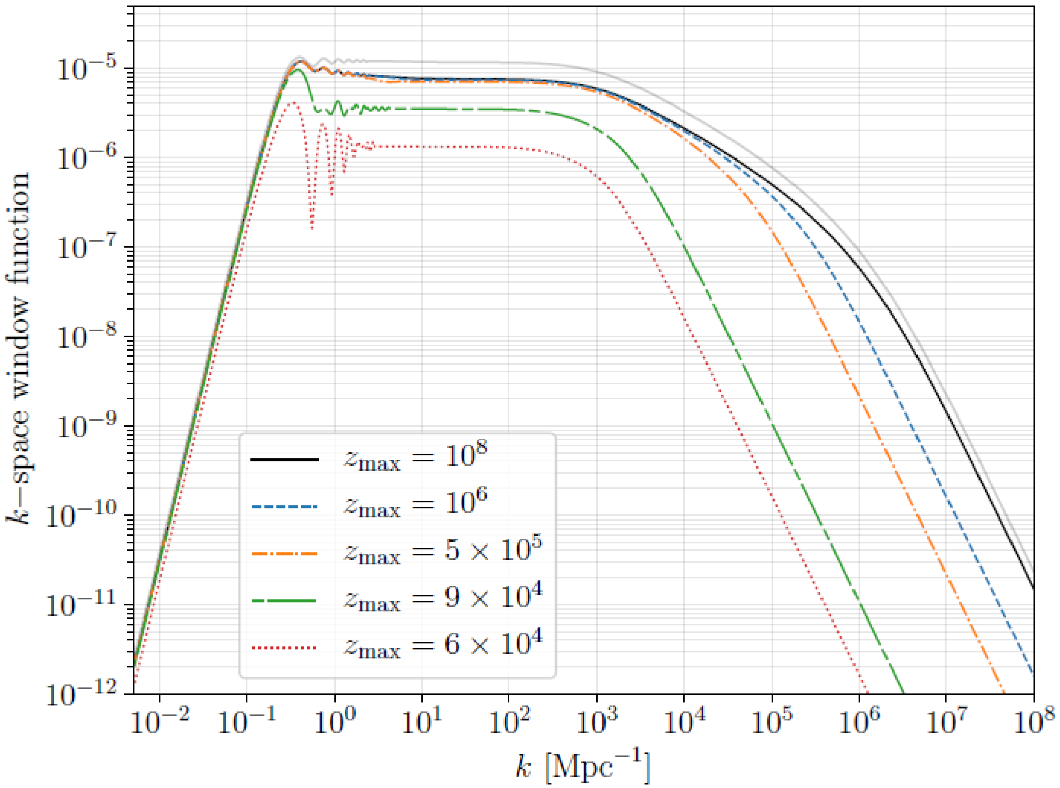


(Fig. from Kite *et al*, 2010.00040)

Spectral distortions and BSM physics II

Need to account that for some scenarios, GWs are produced on sub-horizon scales

$$\langle \mu_{\rm GW} \rangle (z=0) = \int_0^\infty {\rm d}\ln k \int_0^\infty {\rm d}z' W_\mu(k,z) \mathcal{P}_T(k,z)$$



(Kite *et al*, 2010.00040)

Spectral distortions and BSM physics II

Ultra-light “audible” axions

Machado, Ratzinger, Machado, Stefanek; arXiv:1912.01007

$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\tfrac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) \\ -\tfrac{1}{4}X_{\mu\nu}X^{\mu\nu} - \tfrac{\alpha}{4f_\phi}\phi X_{\mu\nu}\tilde{X}^{\mu\nu}\Big]$$

Global U(1) broken at $\Lambda \sim \sqrt{mf}$

When $H < m$ **at** $T_{\rm osc} \approx \sqrt{mM_P}$

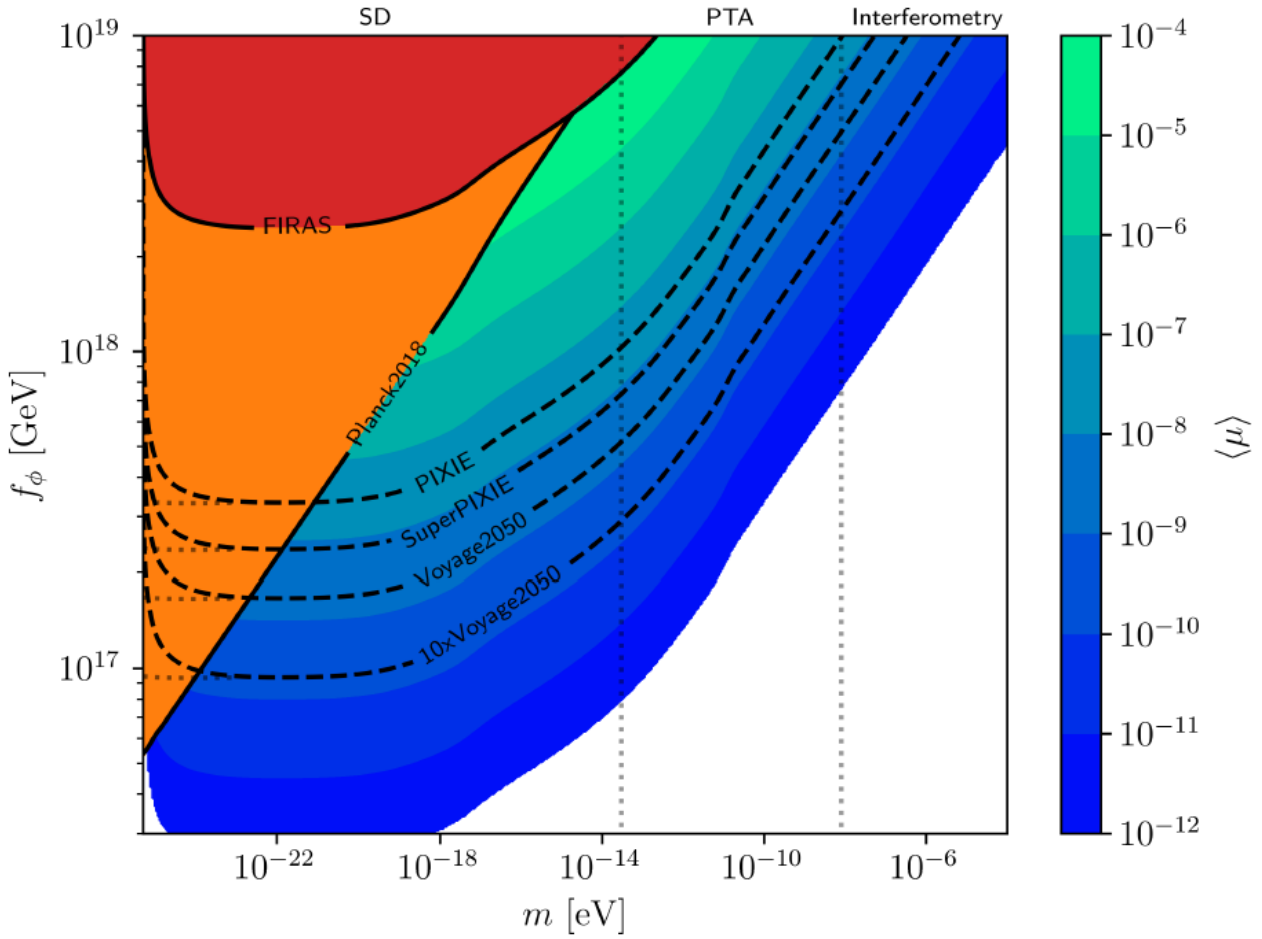
axion oscillations produce dark photons that source chiral GW’s:

$$\Omega_{\rm GW}^{\rm U(1)}(k) = \frac{6.3\Omega_{\rm GW}^{\rm U(1)}(f_{\rm AA})(k/\tilde{k})^{1.5}}{1+(k/\tilde{k})^{1.5}\exp[12.9(k/\tilde{k}+1)]}$$

$$\tilde{k} = 1.3\times 10^{15}\,[f_{\rm AA}/{\rm Hz}]\,{\rm Mpc}^{-1}$$

$$f_{\rm AA} \approx 6\times 10^{-4}{\rm Hz}\left[\frac{\alpha\theta}{66}\right]^{2/3}\left[\frac{m}{10{\rm meV}}\right]^{1/2}$$

$$\Omega_{\rm GW}^{\rm U(1)}(f_{\rm AA}) \approx 1.67\times 10^{-4} g_{\rho,*}^{-1/3}\left[\frac{f_\phi}{M_{\rm pl}}\right]^4\left[\frac{\theta^2}{\alpha}\right]^{4/3}$$



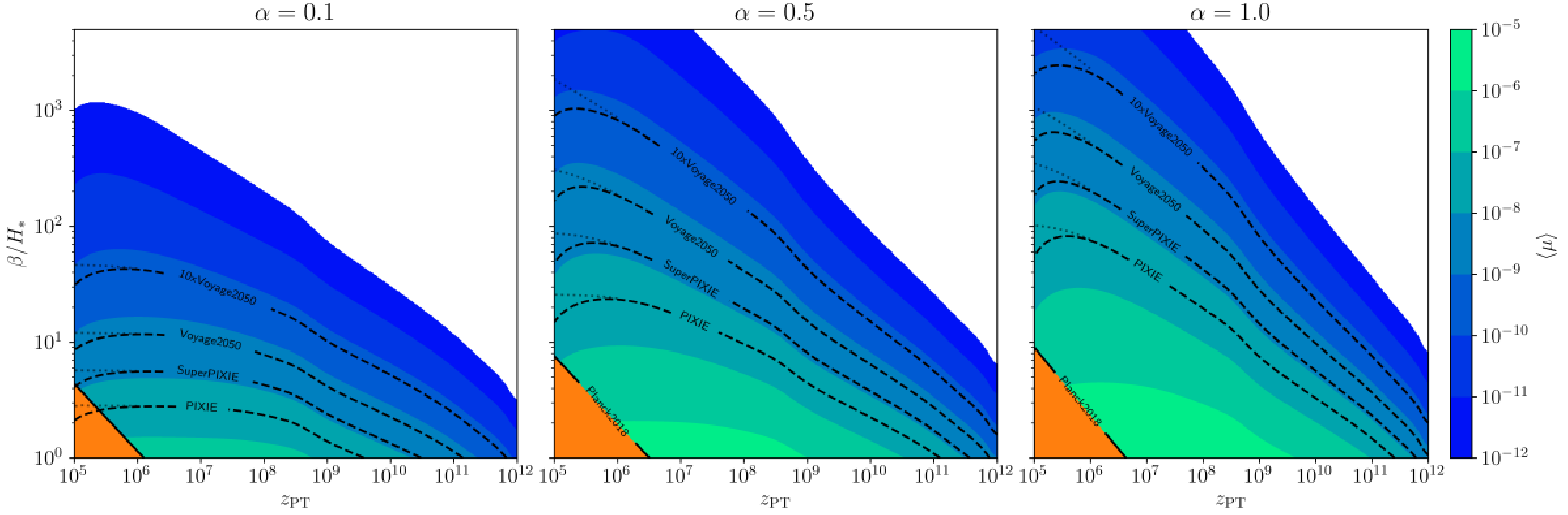
(Kite *et al*, 2010.00040)

Spectral distortions and BSM physics II

First order phase transitions beyond the SM

Cf. review by Caprini and Figueroa; arXiv:1801.04268

Three sources of GWs: bubble wall collisions, MHD turbulence and sound waves



(Kite *et al*, 2010.00040)

$$h^2\Omega^{\rm BC}_{\rm GW}(f) = 1.67\times10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa_{\rm BC}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} \times\left(\frac{0.11v_w^3}{0.42+v_w^2}\right)\frac{3.8\,(f/f_{\rm BC})^{2.8}}{1+2.8\,(f/f_{\rm BC})^{3.8}}$$

$$f_{\rm BC} = 1.65\times10^{-5}{\rm Hz}\left(\frac{0.62}{1.8-0.1v_w+v_w^2}\right)\chi_0$$

$$\chi_0 = \left[\frac{\beta}{H_*}\right]\left[\frac{T_*}{100{\rm GeV}}\right]\left[\frac{g_*(T_*)}{100}\right]^{\frac{1}{6}}$$

$$h^2\Omega^{\rm SW}_{\rm GW}(f) = 2.65\times10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)\left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} \times v_w\left(\frac{f}{f_{\rm SW}}\right)^3\left(\frac{7}{4+3\,(f/f_{\rm SW})^2}\right)^{\frac{7}{2}}$$

$$f_{\rm SW} = 1.9\times10^{-5}{\rm Hz}\,v_w^{-1}\chi_0$$

$$h^2\Omega^{\rm MHD}_{\rm GW}(f) = 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm MHD}\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} \times v_w\frac{(f/f_{\rm MHD})^3}{[1+(f/f_{\rm MHD})]^{\frac{11}{3}}\,(1+8\pi f/h_*)}$$

$$f_{\rm MHD} = 2.7\times10^{-5}{\rm Hz}\,v_w^{-1}\chi_0$$

Spectral distortions and BSM physics II

Cosmic string network collapse:

Leptogenesis via a *B-L* U(1) phase transition in an SO(10) GUT theory.

GWs produced by the subsequent collapse of the string network.

$$h^2\Omega_{\rm GW}^{\rm CS} = h^2\Omega_{\rm GW}^{\rm plateau}\ \min\left[(f/f_*)^{3/2}, 1\right]$$

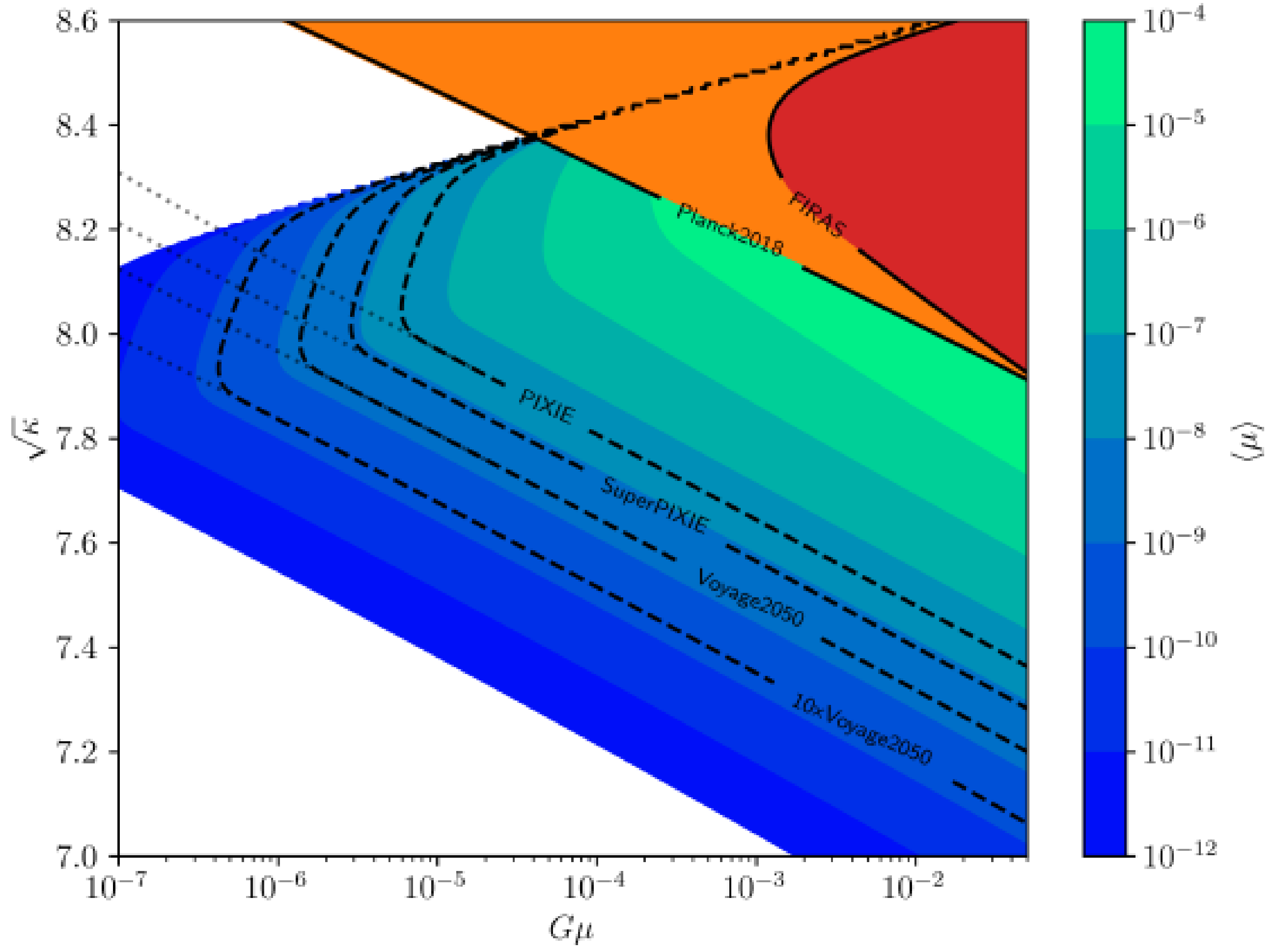
$$f_* = 3\times 10^{14}{\rm Hz}e^{-\pi\kappa/4}\left[\frac{G\mu}{10^{-7}}\right]^{-1/2}$$

$$h^2\Omega_{\rm GW}^{\rm plateau} = 8.04\Omega_{\rm r}h^2\left[\frac{G\mu}{\Gamma}\right]^{1/2}$$

$$z_{\rm collapse} = \left(\frac{70}{H_0}\right)^{1/2}\left(\Gamma\frac{(G\mu)^2}{2\pi G}e^{-\pi x}\right)^{1/4}$$

$$\Omega_\Gamma h^2 = 2.5\times 10^{-5},\ \Gamma \approx 50$$

arXiv:1801.04268; Buchmuller, Domcke, Murayama and Schmitz



(Kite *et al*, 2010.00040)

SCIENCE & EXPLORATION

Voyage 2050 sets sail: ESA chooses future science mission themes

2.3.4 Recommendation

The Senior Committee recommend that ESA should develop a Large mission capable of deploying new instrumental techniques such as gravitational wave detectors or precision microwave spectrometers to explore the early Universe (say $z > 8$). Such a mission would shed light on outstanding questions in fundamental physics and astrophysics, such as how inflation occurred and the Universe became hot and then transparent, how the initial cosmic structures grew, how the first black holes formed and how supermassive black holes came to exist less than a billion years after the Big Bang.

Lorentz center
Workshop @Oort

Mission: Spectro-Polarimetry of the Microwave Sky

31 October - 4 November 2022, Leiden, the Netherlands

Scientific Organizers

- Jens Chluba, University of Manchester
- Jacques Delabrouille, Centre Pierre Binétruy international Laboratory, CNRS / UC Berkeley
- Ema Dimastrogiovanni, University of Groningen
- Subodh Patil, Leiden University
- Daan Meerburg, University of Groningen

Topics

- Spectral Distortion Science
- Targets for Future Missions
- Foregrounds and Foreground Modelling
- Novel Observational Concepts

The Lorentz Center organizes international workshops for researchers in all scientific disciplines. Its aim is to create an atmosphere that fosters collaborative work, discussions and interactions. For registration see: www.lorentzcenter.nl

A backdrop of the cosmic microwave background and a black body, corresponding to perfectly thermal radiation in the early universe, deviations from which we hope to measure in upcoming space based observations. Background image © ESA and the Planck Collaboration. Poster design: SuperNova Studios . NL

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NWO

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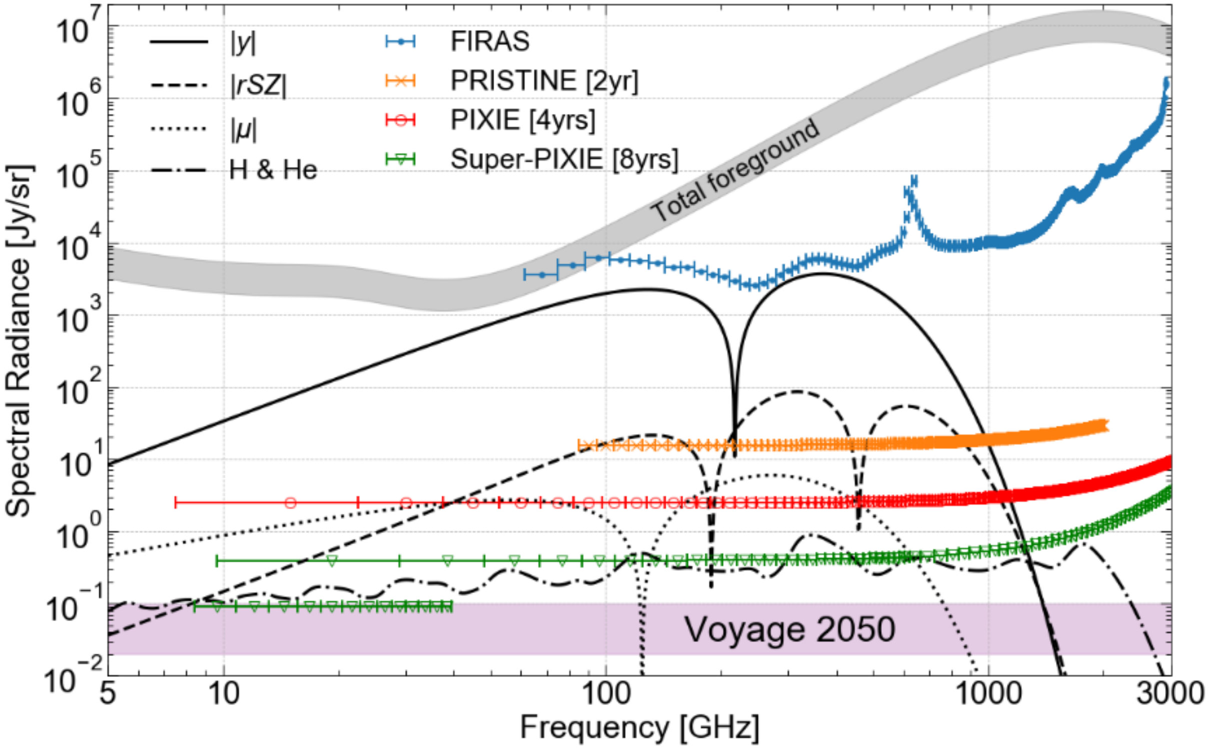
- ~~Calibrating spectrometer to accompany an imager?~~
- Novel experimental concepts (radiometers on chip instead of FTS)?
- Foregrounds issues not insurmountable!
- What signal to target/ optimize mission design?
- Spectrometer on the moon?
- **Go big or go home.**

Mission concepts: beyond FTS

Photo courtesy of NASA (radiometer for Jason atmospheric satellite)

- μ – distortions easier to distinguish at low frequencies.
- Foregrounds (galactic synchrotron) persistent there.



Mission concepts: beyond FTS

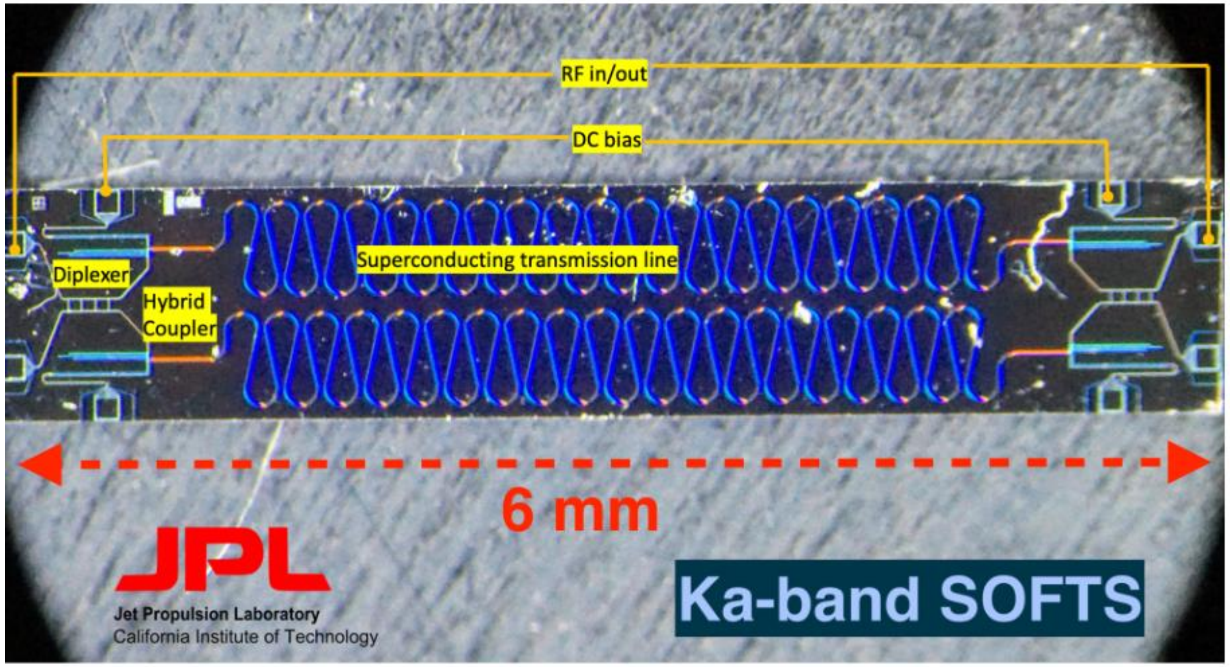
Photo courtesy of NASA (radiometer for Jason atmospheric satellite)

- μ – distortions easier to distinguish at low frequencies.
- Foregrounds (galactic synchrotron) persistent there.
- Need better sensitivty and more frequency channels.
- FTS: loss of sensitivty from binning $\propto \frac{1}{\sqrt{N}}$ (~~PIXIE~~)
- Radiometers don't suffer from this because one can make serial measurements.
- However, size $\propto \lambda$ ... increases cost.

(SO)FTS + calibrator on chip (!)

Ka-SOFTS

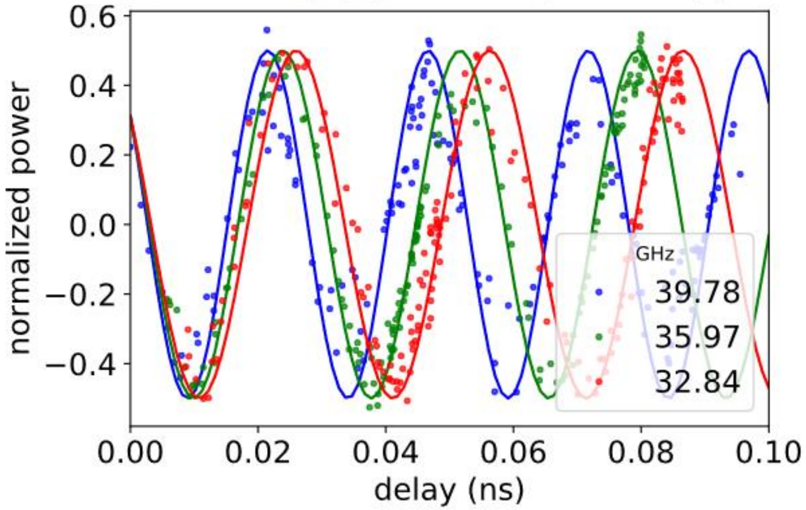
Superconducting On-chip Fourier Transform Spectrometer
Mach-Zehnder 4-port realization



Testing Ka-band (25-40 GHz) SOFTS at Caltech/JPL.

Preliminary measurements

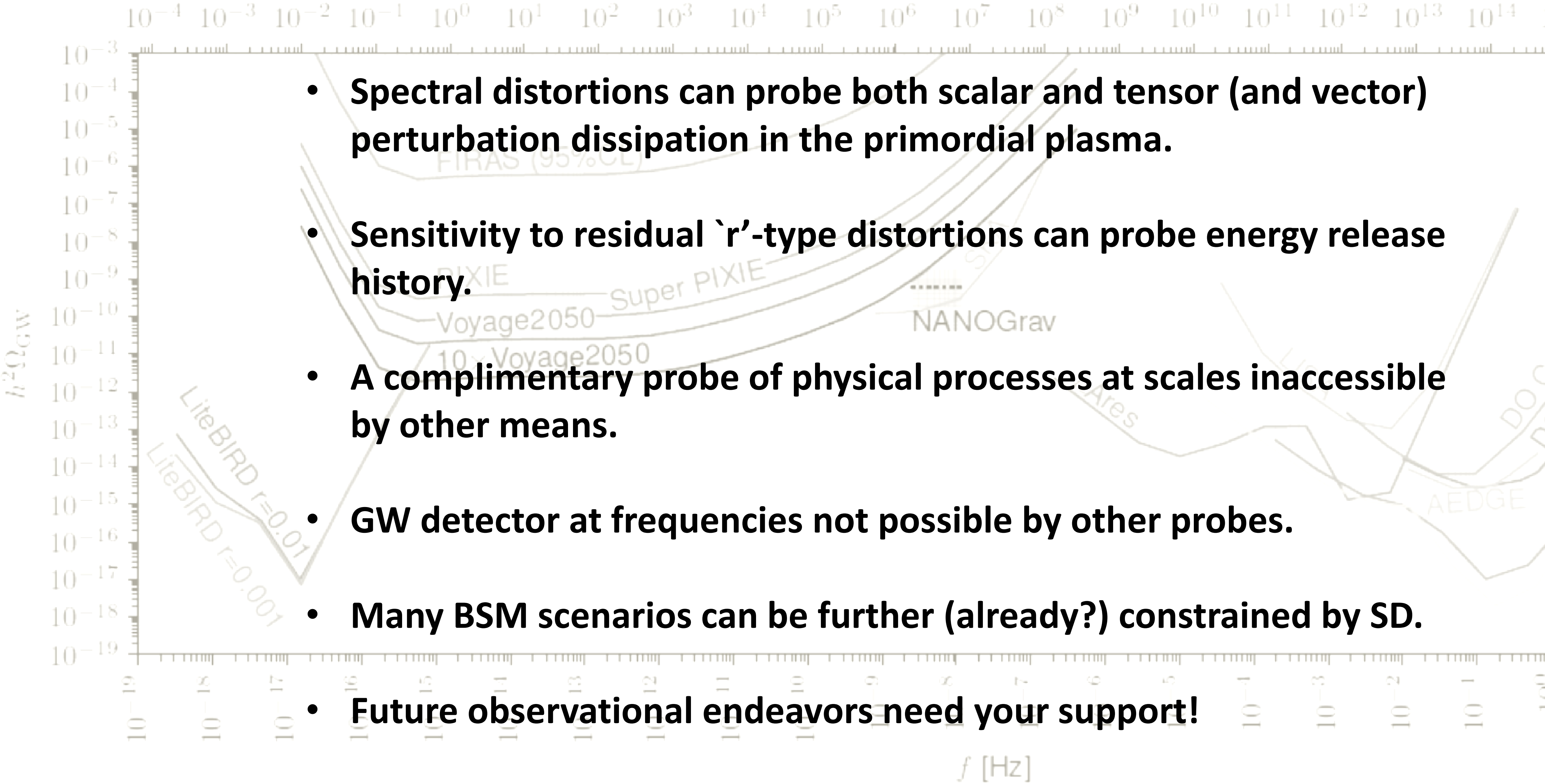
$$P_{FTS} \sim P(\nu)(1 \pm \cos(2\pi\nu\Delta\tau))$$



Expected cosine modulations seen!
Single tone reconstruction indicates formal FTS capabilities.

Slide courtesy of **Ritoban Basu Thakur** (JPL/ Caltech)

Concluding remarks



- **Spectral distortions can probe both scalar and tensor (and vector) perturbation dissipation in the primordial plasma.**
- **Sensitivity to residual `r’-type distortions can probe energy release history.**
- **A complimentary probe of physical processes at scales inaccessible by other means.**
- **GW detector at frequencies not possible by other probes.**
- **Many BSM scenarios can be further (already?) constrained by SD.**
- **Future observational endeavors need your support!**